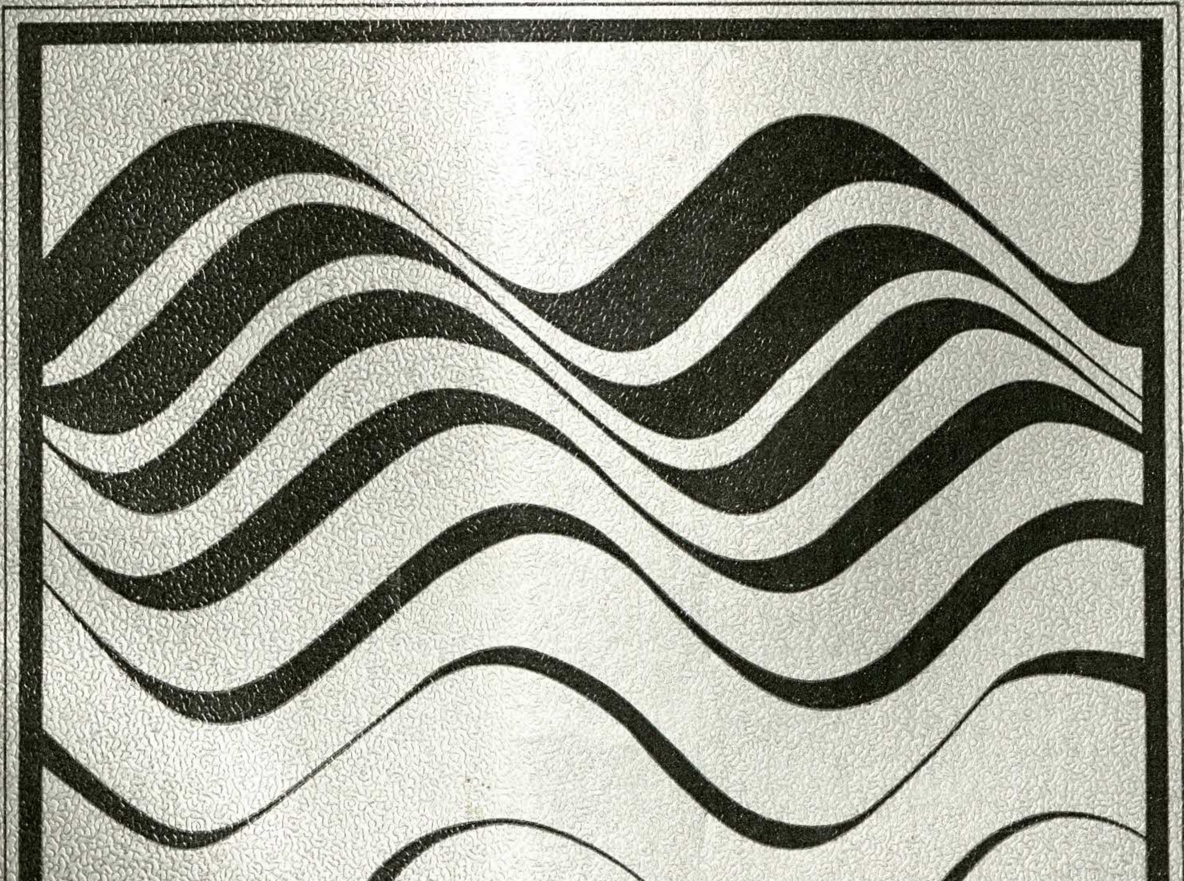
Modern Secondary Physics



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Modern Secondary
PHYSICS

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Preface

The latest ICSE syllabus forms the basis of this new text. Aimed to provide a sound foundation course in Physics, the objectives of the new syllabus have been kept in mind. Neverthless, the authors have chosen a sequence of text affirmed by extensive tests and successful methods which they have employed, and their colleagues throughout the country have corroborated.

A simple and concise style of writing has been followed throughout the text and effort has been made to select examples and problems which are relevant to the students of this age.

Extensive use of illustrations has been made to provide visual summary of the material. The numerous activities suggested should assist teachers and students alike to proceed through the curriculum with enough motivation.

An important consideration in choosing the content and approach was to ensure a smooth transition from the Secondary to the Higher Secondary (+2) stage, and to aid the students taking the National Talent Search Examination.

New Delhi
May 1984

I B KAKAR
B G PITRE

A Note

I have to record with deep regret the sudden demise of I B Kakar who had shared with me, over the past 15 years, the joys and agony of writing books for high school students. By all accounts our books had in no small measure helped generations of students to fare well in exams; and Mr Kakar's contribution in writing these books was significant.

Mr Kakar had completed his task on this book only a week before his fatal heart attack. This book is dedicated to his memory.

15 August 1984

B G PITRE

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1

Simple Measurements

A cricket bowler walks away from the pitch counting equally spaced paces and makes a visible mark on the ground, from where he runs back to the pitch with the same number of similar paces to send the ball to the batsman. If per chance he makes a mistake in not running back with the same paces, he may overstep the bowling line and his delivery may be declared a 'no ball'. The pace-length is his personal unit to measure a distance. As pace length varies from person to person, another bowler, even if he takes the same number of paces, makes his own mark. It is, therefore, evident that pace cannot be taken as a standard to measure a distance.

A quantity like distance which can be measured is called a **physical quantity** and a standard of the same kind with which a physical quantity is compared to measure it, is called a **unit.**

In physics the three physical quantities of length, mass and time are often called **fundamental quantities**, because most other quantities can be derived from these three. The units of length, mass and time are known as **fundamental units**.

A unit must be convenient, easily reproducible and definite. The property for which it is being used should not change.

The process of determining the number of times a physical quantity is bigger or smaller than the unit is called **measurement.** Whether we are in a factory, laboratory or a shop we make measurements of different types. In this scientific age of ours we make accurate and exact measurements with sophisticated instruments. Once a British Scientist Lord Kelvin had said, 'Unless you can measure what you are speaking about, and express it in numbers, you have scarcely advanced to the stage of science'.

Every measurement always contains two terms; (a) a unit with which a quantity is compared and (b) a number which tells the number of times the physical quantity is bigger or smaller than the unit. If we say that the mass of a stone is 1.5 kg, it means that the stone is one and a half times as heavy as a kilogram, which has been taken as a unit. The same stone will be 1500 times as heavy as a gram if gram is taken as a unit. The gram is one-thousandth part of a kilogram. In general, if N_1 and N_2 are the numerical values and U_1 and U_2 are the sizes of the units with which a physical quantity is being compared, then

$$N_1U_1 = N_2U_2$$

1.1 Metric System

Nearly two hundred years ago just after the French Revolution, the new French government asked a group of scientists to work out a simple system of measures to be used throughout France. This group of scientists first estimated the distance from the North Pole to the equator and then divided this distance by 10,000,000. They called the resultant distance a **metre** (in Greek *metron* means measure). Thus we can say that the North Pole is 10,000,000 metres away from the Equator! The **metre** is the fundamental unit of length.

Next the scientists built a bar of platinum and iridium and made two marks on it exactly one metre apart. The distance between these two scratch marks at 0°C is now defined as the **International Metre**. All other metre measures are copies of it.

To avoid difficult arithmetic involved in changing from one unit to another, the metre is divided by tens to get smaller units and is multiplied by tens to get larger units. Thus,

10 millimetres = 1 centimetre
10 centimetres = 1 decimetre
10 decimetres = 1 metre
10 metres = 1 decametre
10 decametres = 1 hectometre
10 hectometres = 1 kilometre

Notice that adding 'kilo' before the unit (metre in this case) multiplies the unit by 1000, whereas adding 'milli' before it divides it by 1000.

Mass is the quantity of matter contained in a body. The metric unit of mass is the **International Kilogram**. This is defined as the mass of a certain cylinder of platinum and iridium kept in the International Bureau of Weights and Measures, in France. This mass is equal to the mass of one cubic decimetre (1000 cm^3) of pure water at 4°C. Its multiples and sub-multiples are as follows.

1000 milligrams = 1 gram
1000 grams = 1 kilogram
100 kilograms = 1 quintal
10 quintals = 1 ton

In all our activities from morning when we get up till we lie in bed at night we are constantly aware of the passage of time. One event leads to another, such as the ringing of school bell and the start of a class. There is a time gap between any two events. Time intervals could be as small as between two steps when we walk, or as large as between the rise and fall of the Mughal empire. When we say that for the first time man landed on the Moon on July 21, 1969 we mean that the event took place 1969 years, 6 months and 21 days after the birth of Christ, which has been taken as the reference event. In this statement, years, months and days are units of time. Second is the standard unit of time whose multiples are minute, hour, day, month and a year.

The **second** is the fundamental unit of time. Its multiples are as follows:

60 seconds = 1 minute
60 minutes = 1 hour
24 hours = 1 day
$365\frac{1}{4}$ days = 1 year

In most measurements, the centimetre (cm), the gram (g) and the second (s) are used as fundamental units. This system of fundamental units is, therefore, called the *C*entimetre-*G*ram-*S*econd system or the C.G.S. system of units.

In most scientific measurements, the *metre* is used as the unit for length, the *kilogram* for mass and the *second* for time. This system of fundamental units is called the *M*etre-*K*ilogram-*S*econd or M.K.S. system of units. The M.K.S. system of units is the most accepted in the world among the various systems.

Derived Quantities

Area, volume and densities, etc., are **derived quantities** which depend upon the fundamental quantities. For example

Area = length^2 and is measured in m^2
Volume = length^3 and is measured in m^3
Density $= \dfrac{\text{mass}}{\text{volume}}$ and is measured in kg/m^3

Table 1.1 gives the names of various derived quantities used in mechanics and their units.

1.2 Measurement of Length

The length (or breadth or width) of any object is measured by comparing it with a standard unit brought close to it. The universally accepted unit of distance is the **metre**. For practical

Table 1.1

Sl. no.	*Quantity*	*Formula*	*Unit*
1.	Area (A)	$A = \text{Length}^2$	m^2
2.	Volume (V)	$V = \text{Length}^3$	m^3
3.	Density (D)	$D = \dfrac{\text{Mass}}{\text{Volume}}$	kg/m^3
4.	Velocity (V)	$V = \dfrac{\text{Distance}}{\text{Time}}$	m/s
5.	Acceleration (a)	$a = \dfrac{\text{Change of velocity}}{\text{Change of time}}$	m/s/s or m/s^2
6.	Momentum (M)	$M = \text{Mass} \times \text{Velocity}$ $= m \times v$	kgm/s
7.	Force (F)	$F = \text{Mass} \times \text{Acceleration}$ $= m \times a$	N (newton)
8.	Work (W)	$W = \text{Force} \times \text{Distance}$ $= F \times S$	J (Joule)
9.	Power (P)	$P = \dfrac{\text{Work done}}{\text{Time}}$	W (Watt)
10.	Moment of force	$\text{Moment} = \text{Force} \times \text{perp. distance}$ $= F \times S$	Nm
11.	Pressure (p)	$p = \dfrac{\text{Force}}{\text{Area}}$ $= \dfrac{F}{A}$	N/m^2

measurements other larger and smaller units are also used (see list in Section 1.1). Of these the most commonly used units and their relation to the metre are as follows.

1 kilometre (km) = 1000 metres (m)
1 metre (m) = 100 centimetres (cm)
= 1000 millimetres (mm)

The smallest measure which can be taken accurately with the help of any instrument is called its **least count**. The least count of a metre or half-metre scale which we use in laboratories is one millimetre.

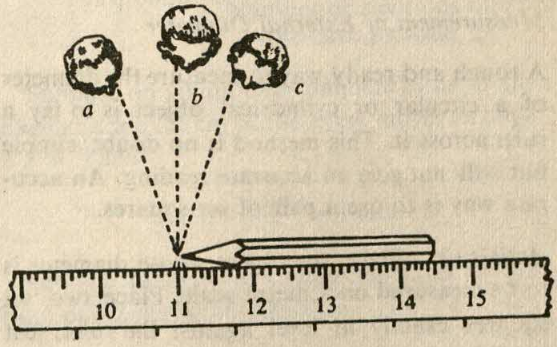


Fig. 1.1

Activity 1. Suppose the length of a pencil is to be measured. Place it along one edge such that one of its ends coincides with any whole division on the scale. Fig. 1.1 illustrates three positions of the eye to observe readings on the scale. Consider the possible errors which occur in our observations due to the two faulty positions (a and c) of the eye. The eye must therefore be placed vertically above the scale mark

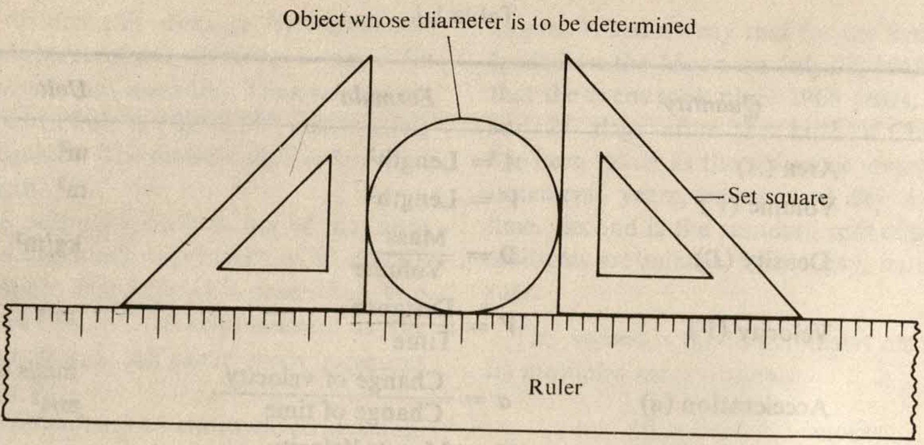


Fig. 1.2

to be read, in order to avoid the *parallax error*.

Note the readings on the scale coinciding with the two ends of the pencil. The difference of these two readings gives us the length of the pencil. In the figure, one of the readings lies between 14.4 cm and 14.5 cm; we cannot possibly say with any degree of confidence whether the reading is 14.44 cm or 14.45 cm or 14.46 cm. The accuracy of our observations is always limited due to such rough estimation.

Since the edges of scales are likely to be worn out due to frequent use, it is advisable to make measurements by difference of observations.

Measurement of External Diameter

A rough and ready way to measure the diameter of a circular or cylindrical object is to lay a ruler across it. This method is no doubt simple but will not give an accurate reading. An accurate way is to use a pair of set squares.

Activity 2. Place the object whose diameter is to be measured on a metre scale. Place two set squares exactly in level against the ruler, just touching the object as shown in Fig. 1.2. The difference in the readings on the scale of the two set squares gives the required diameter. You should take three separate readings, turning the disc or sphere round and using different parts of the ruler.

Activity 3. Another way to measure diameter is to use a pair of **external callipers** (Fig. 1.3). Open the jaws of the callipers and close them over the sphere or cylinder whose diameter is to be measured so that the widest part of the sphere just slips through its jaws. Carefully remove the callipers and place its jaws against a metre scale to read the diameter of the sphere.

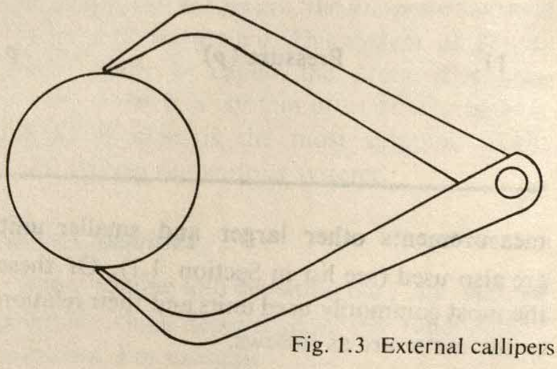


Fig. 1.3 External callipers

Internal diametres of cylinders, tubes and beakers, etc. can best be measured by using a pair of **internal callipers** (Fig. 1.4).

Activity 4. Close the jaws of a pair of internal callipers and then insert it into the beaker or cylinder whose internal diameter is to be measured. Gradually open the jaws until they touch the inner sides of the beaker or cylinder. Remove the callipers and place them against a ruler to read the internal diameter.

Usually the same simple callipers used for measuring external diameter have a second pair

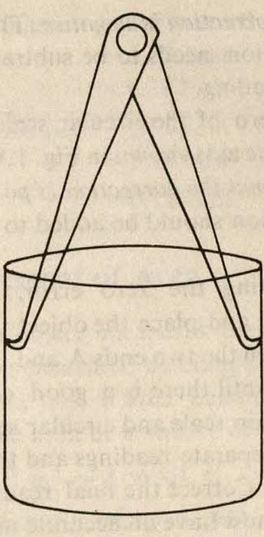


Fig. 1.4 Internal callipers

of jaws at the lower end (Fig. 1.5), made specially for measuring internal diameters.

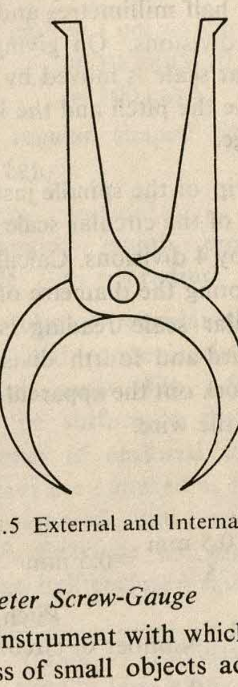


Fig. 1.5 External and Internal callipers

The Micrometer Screw-Gauge

This is an instrument with which we can measure thickness of small objects accurately upto one-hundredth of a millimetre. Its working is based upon the principle of a screw (Fig. 1.6).

When the head of a screw is rotated, its tip moves forward or backward. The linear distance moved by the tip of the screw is directly proportional to the amount of circular movement given to its head. When the head of the screw is given one complete rotation, the tip of the screw moves through a distance equal to the distance between two consecutive threads. This distance is called the **pitch** of the screw. *Pitch is the linear distance moved by the tip of a screw, when its head is rotated through one complete turn. It is equal to the distance between two consecutive threads of the screw.*

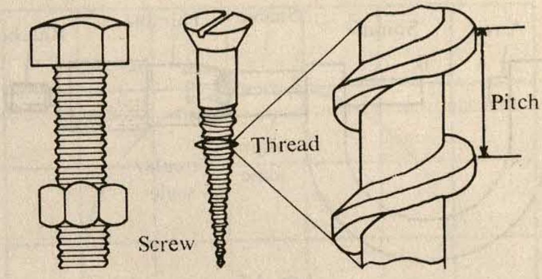


Fig. 1.6

Suppose the head of a screw has a circular disc whose circumference is divided into 100 equal parts. If such a circular scale is rotated through one division, the linear distance moved will be one-hundredth of the pitch. This is the least distance which can be accurately measured with the help of such a screw and is called the **least count** of the screw.

$$\text{Least count} = \frac{\text{Pitch}}{\text{Number of divisions on the circular scale}}$$

Suppose on giving two complete turns to the circular scale the tip of the screw moves through 2 mm. Then

$$\text{Pitch} = \frac{2\text{ mm}}{2} = 1\text{ mm}$$

Let the number of circular divisions on the head of the screw be 100; then

$$\text{Least count} = \frac{1\text{ mm}}{100} = 0.01\text{ mm} = 0.001\text{ cm}$$

The micrometer screw-guage employs this principle to measure small thicknesses very accurately. The main features of this instrument are shown in Fig. 1.7. It consists of an accurately cut screw fitted axially into a tube

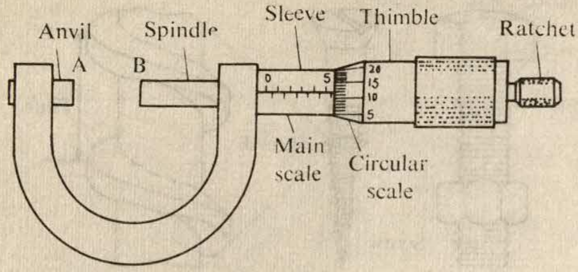
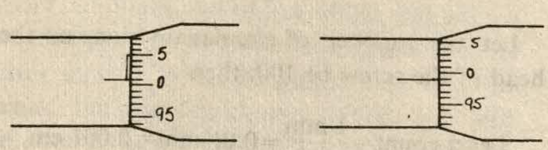


Fig. 1.7

attached to a steel frame. On the tube a fixed millimetre scale is engraved and is called the **main scale**. The screw is provided with a thimble on whose edge usually 100 equal divisions are made. This is called the **circular scale**. To measure the thickness of an object, it is placed against the **anvil** (Fig. 1.7) and the screw is rotated so that the tip of the **spindle** (Fig. 1.7) just touches the object. If a person applies too much force to the screw after the tip touches the object, the reading can be wrong. To avoid this, the circular scale is provided with a ratchet head. On rotating the ratchet head, when the tip of the screw touches against the object being measured, the ratchet will twist but the tip will not move ahead.

Before taking any measurements, the zero error of the instrument has to be determined.

Activity 5. Twist the ratchet head until the end of the anvil just touches the tip of the spindle. When this happens you will hear a 'click' showing that the right contact has been made. Now check for zero error. If the zero on the circular scale is in line with the zero on the main scale then the instrument has no zero error.



(a) Positive zero error (b) Negative zero error

Fig. 1.8

If the zero on the circular scale fails to reach the reference line, or is below it, as shown in Fig. 1.8(a), the instrument has *positive zero error and correction is negative*. This means that the correction needs to be subtracted from the apparent reading.

If the zero of the circular scale is above the reference line as is shown in Fig. 1.8(b), the *error is negative and the correction is positive*. Hence the correction should be added to the apparent reading.

After noting the zero error, unscrew the ratchet head and place the object to be measured in between the two ends A and B. Screw back the ratchet until there is a good contact. Note down the main scale and circular scale readings. Take three separate readings and then work out the average. Correct the final reading for zero error. You now have an accurate measure of the thickness or diameter of the object upto one-hundredth of a millimeter.

EXAMPLE 1. The linear scale of a screw-gauge is divided into half millimetres and the circular scale has 50 divisions. On giving 5 complete turns, the linear scale is moved by 5 such divisions. Calculate the pitch and the least count of the screw guage.

When the tip of the spindle just touches the anvil, the zero of the circular scale is below the reference line by 4 divisions. Calculate the zero error. While noting the diametre of a wire suppose the circular scale reading is 42 and it is between the third and fourth divisions on the linear scale. Work out the apparent and corrected diametre of the wire.

Solution

(a) $\text{Pitch} = \frac{5 \times 0.5 \text{ mm}}{5} = 0.5 \text{ mm}$

(b) $\text{Least count} = \frac{\text{Pitch}}{\text{Number of circular divisions}}$

$= \frac{0.5 \text{ mm}}{50} = 0.01 \text{ mm}$

(c) $\text{Zero error} = +4 \times 0.01 \text{ mm}$

$= +0.04 \text{ mm}$

(d) $\text{Zero correction} = -\text{zero error}$

$= -0.04 \text{ mm}$

(e) Apparent diameter = 1.5 mm + 0.42 mm
= 1.92 mm
= 0.192 cm

(f) Corrected diameter = 1.92 mm − 0.04 mm
= 1.88 mm
= 0.188 cm

1.3 Measurement of Area

The **area** of an object measures the extent of its surface. It is measured by comparing it with 1m^2, which is the unit of area commonly used. It is equal to the area of a square of 1m side.

$$1 \text{ m}^2 = 1 \text{ m} \times 1 \text{ m}$$

The smaller units of area are 1 cm^2 and 1 mm^2 and they are interrelated as below:

$$\begin{aligned} 1 \text{ m}^2 &= 1 \text{ m} \times 1 \text{ m} \\ &= 100 \text{ cm} \times 100 \text{ cm} \\ &= 10{,}000 \text{ cm}^2 \end{aligned}$$

$$\begin{aligned} 1 \text{ cm}^2 &= 1 \text{ cm} \times 1 \text{ cm} \\ &= 10 \text{ mm} \times 10 \text{ mm} \\ &= 100 \text{ mm}^2 \end{aligned}$$

The area of regular shaped bodies can be determined as below:

Area of a square = side^2
Area of a rectangle = length × breadth
Area of a circle = $\pi \times \text{radius}^2$

Area of a regular or irregular shaped surface can be determined conveniently by using a centimetre graph paper (Fig. 1.9). Trace the boundary of the surface on the graph paper. Count the number of enclosed squares; more than half squares are counted as full while less than half are ignored. Since each square is equal to 1 cm^2, therefore the number of full and more than half enclosed squares gives the area of the surface.

Check the result by calculating the area of the circle used in Fig. 1.9 by measuring its radius and using the formula given above.

1.4 Measurement of Volume

Have you heard the story of a thirsty crow which found a pitcher containing some water but could not reach its level? It raised the level of water by dropping pebbles in it. It was clever enough to realise that no two objects occupy the same space at the same time; that pebbles displace water as they sink to the bottom.

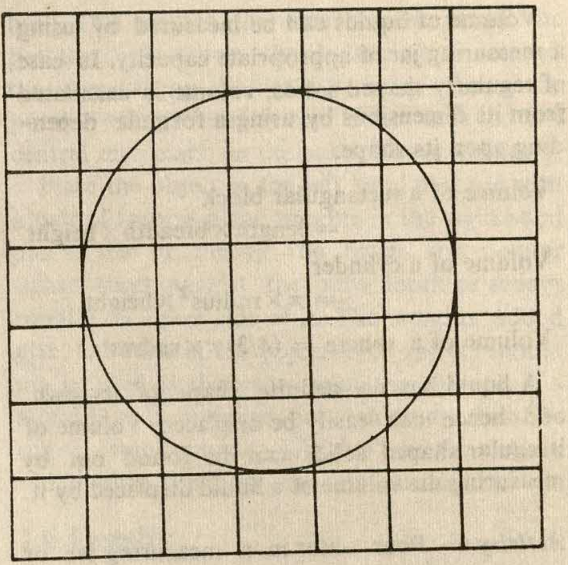


Fig. 1.9

The space which an object occupies is called its **volume**. A cube of side 1 cm has a volume 1 cm^3 (1 cm × 1 cm × 1 cm); a cube of side 1 m has a volume 1 m^3. These are taken as standards for volume measurement and are related as follows:

$$\begin{aligned} 1 \text{ m}^3 &= 1 \text{ m} \times 1 \text{ m} \times 1 \text{ m} \\ &= 100 \text{ cm} \times 100 \text{ cm} \times 100 \text{ cm} \\ &= 1{,}000{,}000 \text{ cm}^3 \end{aligned}$$

The volume of liquids is usually measured in a unit called **litre** which is equal to 1000 cm^3. Hence,

1 litre = 1000 cm^3
Also, 1 m^3 = 1000 litres
Since 1 litre = 1000 millilitres (ml)
1 ml = 1 cm^3

Milkmen usually carry cans which are marked 1 litre, 500 ml and 250 ml. Milk is distributed by these cans by filling them completely. The capacity of a container is the maximum volume of liquid it can fill. Milk bottles provided in some places usually have a capacity of half litre.

Volume of liquids can be measured by using a measuring jar of appropriate capacity. In case of regularly shaped solids, volume is calculated from its dimensions by using a formula depending upon its shape.

Volume of a rectangular block
$= \text{length} \times \text{breadth} \times \text{height}$

Volume of a cylinder
$= \pi \times \text{radius}^2 \times \text{height}$

Volume of a sphere $= (4/3)\,\pi \times \text{radius}^3$

A liquid has no definite shape of its own, and hence can easily be displaced. Volume of irregular shaped solids can be found out by measuring the volume of a liquid displaced by it.

Activity 6. Pour water in a measuring jar or a graduated cylinder and note its volume by viewing it normally (see Fig. 1.10). In case of water, the reading is noted against the lower meniscus, while in coloured liquids, the volume is read against the upper meniscus. Now tie the irregular solid with a string and lower it slowly into water till it is completely immersed. Record the new level of water. The difference between the two readings gives the volume of the solid.

Activity 7. Another method of finding out the volume of an irregular solid is by using a displacement or overflow can. Fill the can completely till water overflows through the side tube. Now hold a measuring jar under the side tube and slowly lower the solid in the water till it is completely immersed (Fig.1.10). The solid will displace water equivalent to its own volume; this water is collected in the measuring jar. The volume of water displaced gives the volume of the solid.

If a solid floats in water, for example a cork piece, its volume cannot be determined by the above displacement method. In such a case, a heavy object called a **sinker** is used. When the cork is tied to the sinker, the combination sinks in water.

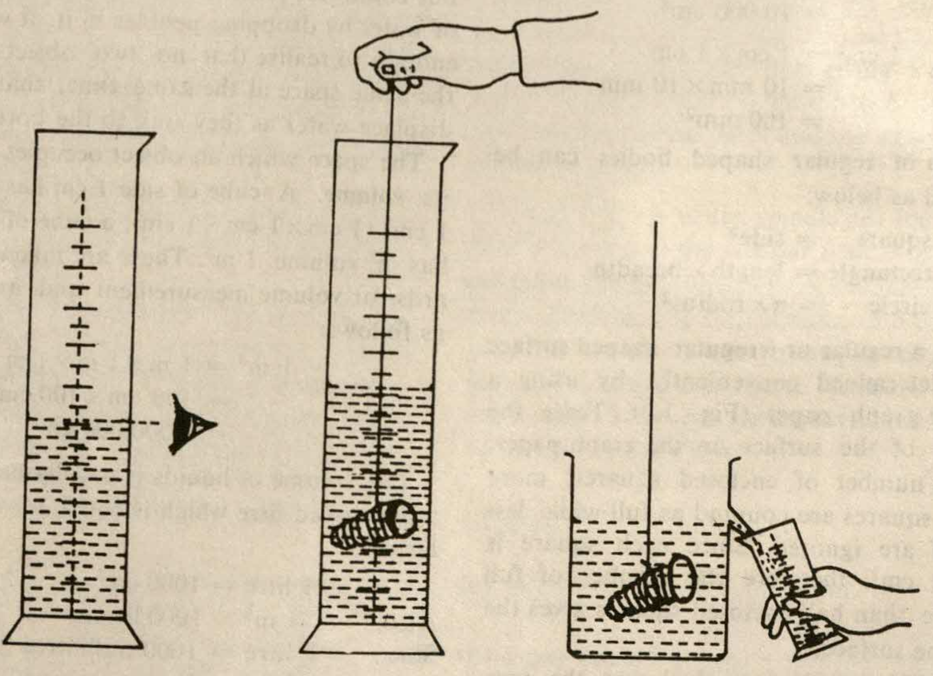


Fig. 1.10

Activity 8. Pour water in a measuring jar. Tie the sinker to a thread and lower it in water till it is completely immersed. Note the reading. Now tie the cork piece and the sinker together and lower them in water till both are completely immersed; note the reading on the jar again. The second reading is more than the first by an amount equal to the volume of the cork piece. In this experiment it is essential that the water is not spilled over when the sinker is raised up for tying the cork.

1.5 Measurement of Mass

Mass is the quantity of matter contained in a body and is measured in kilogram with an ordinary beam balance or a physical or laboratory balance. Kilogram (kg) is the unit of mass whose multiples or sub-multiples are given below:

1 ton = 10 quintals
1 quintal = 100 kg
1 kg = 1000 grams (g)
1 g = 1000 milligrams (mg)

A physical balance is used when a greater degree of accuracy is needed, e.g. for finding the mass of a piece of gold or diamond.

Activity 9. Fig. 1.11 shows a physical balance used in a laboratory. Adjust the levelling screws provided at the base so that the base is horizontal. In this position the plumb-line is just above the pointed end of a nob fixed vertically on the base. This ensures the free movement of the pointer. Now adjust the balancing screws so that on raising the beam by using a lever, the pointer swings equally on either side of the central zero mark on the scale. Lower the beam.

Place the object in the left hand pan and with a pair of forceps place weights in the right hand pan so that on raising the beam, the pointer either stays against the zero mark or swings equally on either side of it. The weights added give the mass of the object. Hot objects should not be used as these may spoil the balance. If a liquid is to be weighed, its container must be wiped from outside. Weights should only be added when the beam has not been raised.

1.6 Density

Is wood heavier than iron? Most of us would say 'no'. But this is not always true. A wooden desk is heavier than a nail. This is because the volume of the wooden desk is much more than that of the nail. We can safely say, however, that iron is heavier than an equal volume of wood.

The ratio of mass to the volume of a material is called its density. *The mass per unit volume of a material is known as its* **density.**

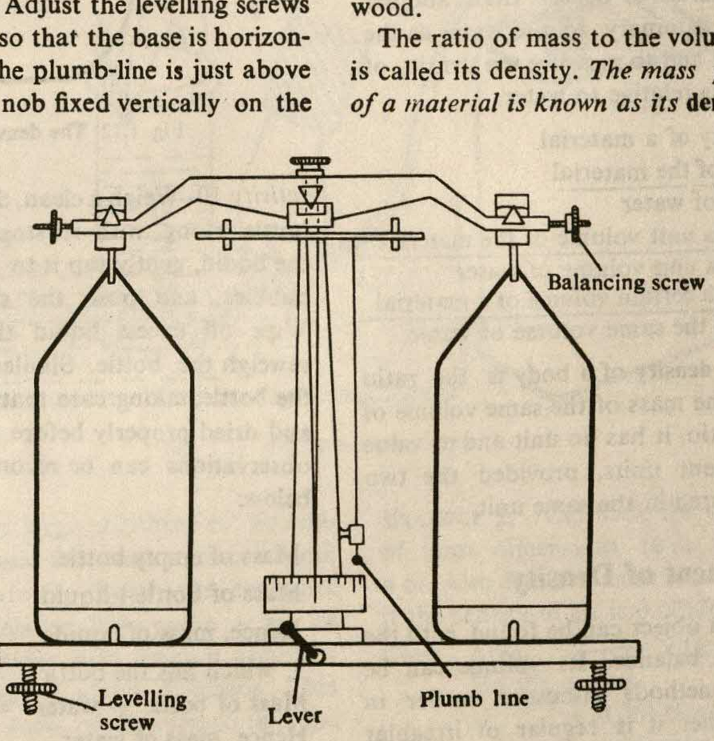


Fig. 1.11 **Physical balance**

$$\text{Density (kg/m}^3) = \frac{\text{mass of an object (kg)}}{\text{volume of the object (m}^3)}$$

If the mass of an object is measured in grams and its volume in cm³, then its density is in g/cm³. Since 1 cm³ of water is found to weigh 1 g, we have

$$\text{Density of water} = \frac{1\text{ g}}{1\text{ cm}^3}$$

$$= \frac{1/1000\text{ kg}}{1/1,000,000\text{ m}^3} = \frac{1,000,000\text{ kg/m}^3}{1000}$$

$$= 1000\text{ kg/m}^3$$

Also

$$\text{density of water} = \frac{1\text{ g}}{1\text{ cm}^3} = \frac{1/1000\text{ kg}}{1/1000\text{ litre}}$$

$$= 1\text{ kg/litre.}$$

Similarly we can say that density of mercury is 13.6 g/cm³, 13.6 kg/litre or 13,600 kg/m³.

1.7 Relative Density

While talking of density, another term known as relative density (R.D.) is more often used. The relative density indicates how many times a particular material is denser than another material. It is customary to use water as the standard material and to measure the density of all other materials relative to water.

Relative density of a material

$$= \frac{\text{density of the material}}{\text{density of water}}$$

$$= \frac{\text{mass of a unit volume of the material}}{\text{mass of a unit volume of water}}$$

$$= \frac{\text{mass of a certain volume of a material}}{\text{mass of the same volume of water}}$$

Hence **relative density** of a body is the ratio of its mass to the mass of the same volume of water. Being a ratio, it has no unit and its value is same in different units, provided the two masses are measured in the same unit.

1.8 Measurement of Density

The mass of an object can be found with the help of a beam balance. Its volume can be determined by methods discussed earlier in Section 1.3, whether it is regular or irregular in shape, or it floats on water. Hence, density can be determined by dividing mass with volume.

Density Bottle

The density bottle is a specially designed bottle with which we can find R.D. of liquids and powders fairly accurately. The essential feature of the bottle is that it has a glass stopper, which fits accurately into its neck and has a hole through its middle to allow excess liquid to overflow (Fig.1.12). This allows the bottle to be filled to the top. Hence, the capacity of the bottle remains the same no matter what liquid is taken inside it.

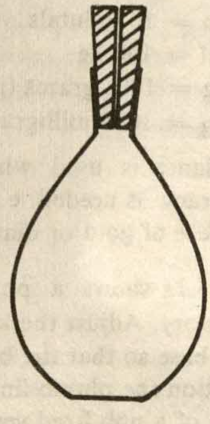


Fig. 1.12 **The density bottle**

Activity 10. **Weigh a clean, dry and empty density bottle along with its stopper. Fill it fully with the liquid, gently tap it to drive away any air bubbles, and push the stopper into the neck. Wipe off excess liquid that overflows, and reweigh the bottle. Similarly, weigh water in the bottle, taking care that the bottle is cleaned and dried properly before water is poured. The observations can be recorded systematically as below:**

Mass of empty bottle	**= x grams (say)**
Mass of bottle + liquid	**= y grams (say)**
Hence, mass of liquid which fills the bottle	**= $(y - x)$ grams**
Mass of bottle + water	**= z grams (say)**
Hence, mass of water which fills the bottle	**= $(z - x)$ grams**

Hence, R.D. of liquid

$$= \frac{\text{mass of liquid}}{\text{mass of equal volume of water}}$$

$$= \frac{y-x}{z-x}$$

Density of Air

It is difficult to find the density of air or a gas because they weigh very little. A very large volume will, therefore, have to be taken. This problem can be solved by taking a highly compressed gas in a fairly strong container. But this poses another problem of finding its volume at atmospheric pressure. We therefore use a specially designed technique and apparatus as shown in Fig. 1.13.

Take a jar of known volume, fill it completely with water and invert it in a trough containing water, taking care to see that no air bubbles are trapped in the jar. Join the tap of the polythene tin or container containing compressed air to a rubber tubing whose other end is held under the mouth of the inverted jar. Gradually release the compressed air. Bubbles of air will be seen rising up in the jar. They will displace water and collect at the top. When all the water has been displaced, close the tap. Fill the jar again with water and repeat the process till you get as many jars filled with air at atmospheric pressure as you can. This number multipled by the capacity of the jar, gives the volume of air that has come out of the can. Mass divided by the volume gives the density of air at atmospheric pressure.

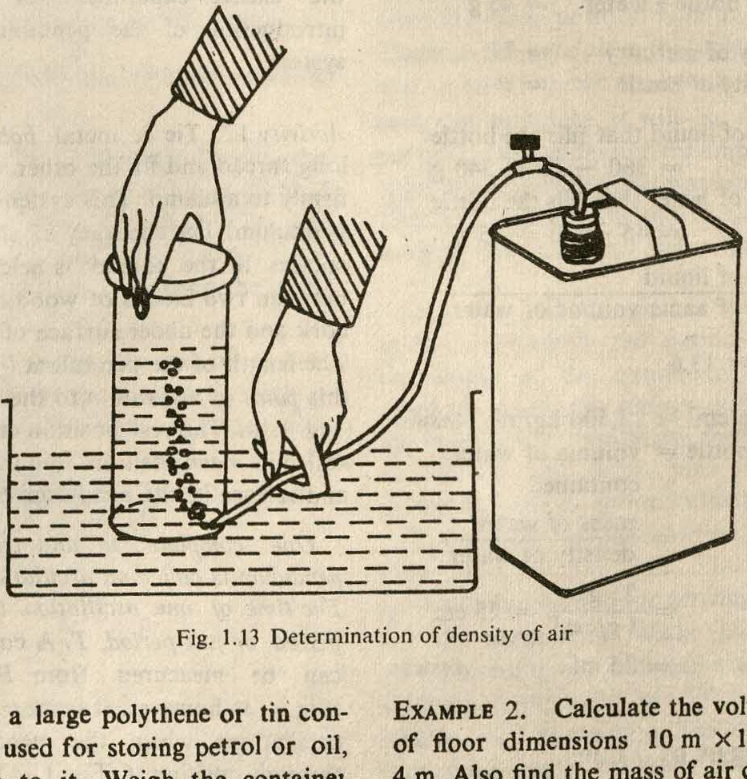


Fig. 1.13 Determination of density of air

Activity 11. Take a large polythene or tin container, like those used for storing petrol or oil, and attach a tap to it. Weigh the containei on a large beam balance. Now pump a lot of air into the container and weigh it again; its mass should increase by about 5 grams. This increase gives the mass of air pumped into the container from outside.

EXAMPLE 2. Calculate the volume of a room of floor dimensions 10 m × 12 m and height 4 m. Also find the mass of air contained by it if the density of air is 0.00126 g/cm³.

Given Area $= 10\text{m} \times 12\text{ m} = 120\text{ m}^2$

Height $= 4$ m

$d = 0.00126 \times 1000$

$= 1.26\text{ kg/m}^3$

To find Volume = ?
Mass of air = ?

Solution Since Volume = area × height
$\therefore$ Volume = 120×4
= 480 m^3 ***Answer***

As Mass = volume × density
$\therefore$ Mass = 480×1.26
= 604.8 kg. ***Answer***

EXAMPLE 3. A bottle full of water weighs 45 g; when full of mercury it weighs 360 g. If the empty bottle weighs 20.0 g, calculate the density of mercury. What is the capacity of the bottle?

Given Mass of empty bottle = 20.0 g
Mass of bottle + mercury = 360.0 g
Mass of bottle + water = 45 g

To find Density of mercury = ?
Capacity of bottle = ?

Solution Mass of liquid that fills the bottle
= 360 − 20 = 340 g
Mass of water that fills the bottle
= 45 − 20 = 25 g

$$\text{R.D.} = \frac{\text{mass of liquid}}{\text{mass of same volume of water}}$$

$$= \frac{340}{25} = 13.6$$

Density = 13.6 g/cm^3 or 13,600 kg/m^3 ***Answer***
Capacity of the bottle = volume of water contained

$$= \frac{\text{mass of water}}{\text{density of water}}$$

$$= \frac{25\text{ g}}{1\text{ g/cm}^3} = 25\text{ cm}^3$$

= 25 ml ***Answer***

1.9 Measurement of Time

Unlike the units of length, the unit of time cannot be stored; it must therefore repeat itself. A system which repeats itself at regular intervals of time is called a **periodic system**. The measurement of time is really the comparison of an unknown time interval with a standard time interval of a periodic system.

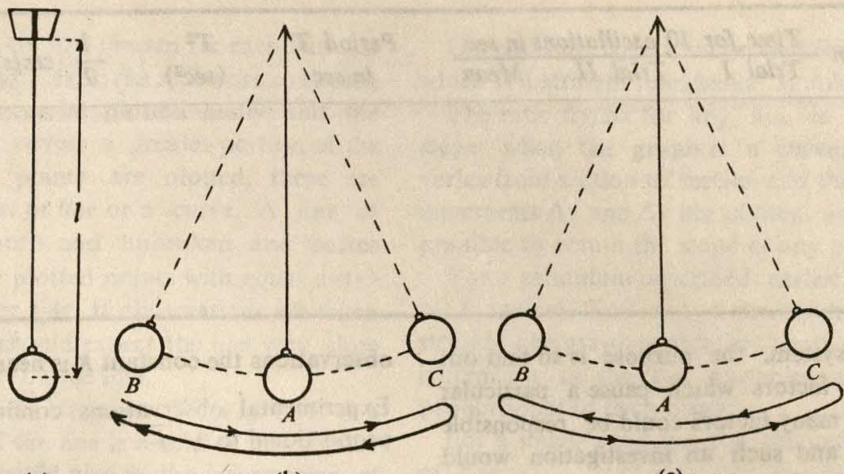
One of the *natural* periodic phenomena known to men from early times is the repetition of day and night due to the spin of the Earth round its axis as it revolves round the Sun. As the Earth's orbit around the Sun is not quite circular, a solar day varies slightly in duration over the year.

Sun dials, water and sand clocks were used in earlier times for measurement of time intervals. These were inconvenient to use because whereas the sun dial could not be moved from place to place, water and sand clocks had to be attended to regularly. The real advancement in the construction of clocks was made only after the classic experiments of Galileo and the introduction of the pendulum as a periodic system.

Activity 12. Tie a metal *bob* to one end of a long thread and fix the other end of the thread firmly to a clamp. This system is called a simple pendulum. The accuracy of the experiment increases if the thread is held at the top firmly between two blocks of wood or two pieces of cork and the under surface of these is levelled. The length of the pendulum *l* is measured from this *point of suspension* to the centre of the bob (Fig. 1.14). The rest position of the bob, *A*, is called its *mean* position. Pull the bob to one side and release it; the pendulum begins to swing.

One complete to and fro movement of a pendulum is called an oscillation or a vibration. The time of one oscillation is called its time period, or just period, T. A complete oscillation can be measured from *B* to *C* and back (Fig. 1.14); however, it is more accurate to count oscillations when the pendulum is passing through position *A* (Fig. 1.14), because at this point its speed is greatest and hence the error in observing the position while clicking the watch or clock is the least.

Oscillate the pendulum and start a stop watch when the bob crosses the mean position *A*.



(a) (b) (c)

Fig. 1.14

Stop the clock when the bob again passes the position *A* after 10 complete oscillations.

Hence, find the average time for one complete oscillation, *T*.

Using a bob of different mass but keeping the length same, repeat the experiment and check if the period depends on its mass. You will observe that within experimental accuracy there is no change in the period on altering the mass.

Activity 13. Fig. 1.15 shows the use of a protractor to displace the pendulum through a measured angle from the mean position. The distance *a* through which the bob is displaced from the mean position is called the *amplitude*. Displace the pendulum through various angles and release the bob to determine the period in each case as before. It will be found that the period is independent of the amplitude when the angle is kept small. This was one of the many Galileo's experiments in which he used a lamp hanging from the roof top as his pendulum.

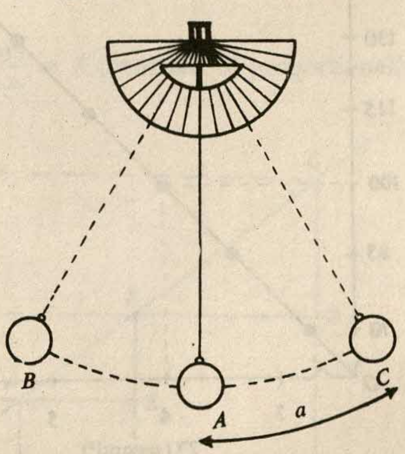


Fig. 1.15

Activity 14. The purpose of this experiment is to find out whether the period depends upon the length of the pendulum. Take about 6 observations for the periods as before, changing the length of the pendulum from about 70 cm to 140 cm and record your observations in a systematic way as shown in the table.

You will notice that additional columns have been provided in the table to record calculations required for arriving at conclusions of the experiment. Make all the necessary calculations; it will be found that *T* increases as *l*. However, the ratio of l/T is not constant; instead l/T^2 is constant. The expression means that as the length is doubled, say from 70.0 cm to 140.0 cm, $(\text{period})^2$ becomes double the initial value.

1.10 Variable and Function

When experiments are conducted to investigate

Length in cm	Time for 10 oscillations in sec			Period T in sec	T^2 (sec^2)	$\frac{l}{T}$ (cm/s)	$\frac{l}{T^2}$ (cm/s^2)
	Trial I	Trial II	Mean				
70.0							
85.0							
100.0							
115.0							
130.0							
140.0							

a physical system, the purpose is to find out the various factors which cause a particular effect. Since many factors could be responsible for an effect and such an investigation would be too complex for a clear understanding of the system, we conduct *controlled* experiments in which an effort is made to keep constant all except one factor which possibly influence the system. For example, in the above experiments we identified three factors: mass of the bob, amplitude and length, which might influence its period. In each experiment, two of these were kept constant so that the dependence of the period on the third could be investigated.

The factor which is varied independently (the cause) is called a *controlled variable* while the factor in which a change is observed (the effect) is called a *function* or *dependent variable.* In Activity 10, length of the pendulum l is the controlled variable while time period T is the function or dependent variable.

1.11 Proportionality

Observations of the pendulum experiment show that T^2 doubles as the length is made twice and trebles when the length becomes three times. We say that (period)^2 is directly proportional to the length, or varies directly as the length. In mathematical language.

$$l \propto T^2 \text{ or } T \propto \sqrt{l}$$

or $$\frac{l}{T^2} = \text{constant}$$

or $$l = KT^2$$

The symbol '$\propto$' means 'is proportional to' or 'varies directly as'. According to experimental observations the constant K is nearly 24.8 cm/s^2.

Experimental observations confirm that T is proportional to $\sqrt{l}$.

1.12 Graphs

A pictorial exhibition of the relationship between two variables is called a graph. According to an old saying 'one picture is worth a thousand words'. Graphs are used extensively in presenting scientific information because of the quick insight they give into the relationships between variables of a system, and their usefulness as a tool in reshaping the information.

To show the relationship between l and T^2 according to the information gathered earlier,

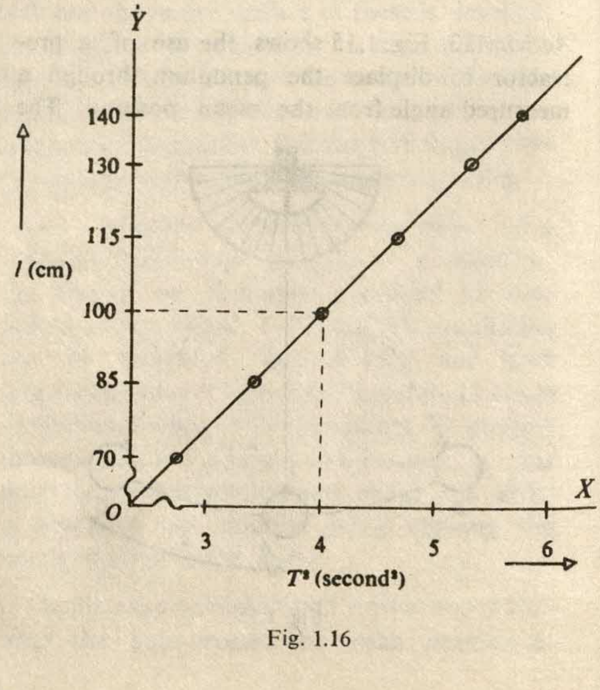


Fig. 1.16

suitable scales are first chosen for each variable along the X and Y axes; the scales are so chosen that the points can be plotted easily and the line or curve covers a greater portion of the graph. When points are plotted, these are joined by a *best fit line* or a curve. A line of best fit is smooth and unbroken and passes close to all the plotted points with equal distribution on either side. If observations are taken carefully, one should expect the line very close to all the points on the line.

The graph of l against T^2 (Fig. 1.16) is a straight line. If the line is extended upwards or downwards it could give us the information of period when the length is greater than 140 cm or less than 70 cm.

The Slope

Let us take three points A, B and C on the straight line whose coordinates are (x_1, y_1), (x_2, y_2) and (x_3, y_3) respectively. Then

$$BE = y_2 - y_1 = \Delta y_1$$
$$AE = x_2 - x_1 = \Delta x_1$$
$$CD = y_3 - y_2 = \Delta y_2$$
$$BD = x_3 - x_2 = \Delta x_2$$

where Δ denotes 'a small change of' or 'a small difference of'.

Since the two triangles ABE and BCD are similar whatever the coordinates of A, B and C may be,

$$\frac{\Delta y_2}{\Delta x_2} = \frac{\Delta y_1}{\Delta x_1} = K \text{ (constant of proportionality)}$$

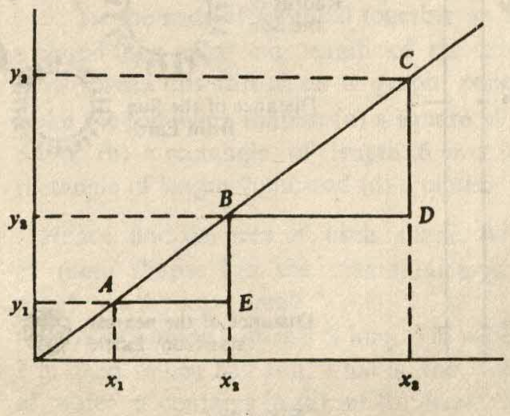


Fig. 1.17

Generalising, $\Delta y/\Delta x$ = constant for any graph which is a straight line; hence $\Delta y \propto \Delta x$.

The ratio $\Delta y/\Delta x$ for any line is called the **slope**; when the graph is a curve, the slope varies from section to section and therefore the increments Δy and Δx are chosen as small as possible to obtain the slope at any point.

For a pendulum described earlier, a graph of l against T is not a straight line. Thus a straight line graph is obtained only when the increments in the two variables are directly proportional to each other.

For a *simple pendulum* the theoretical value of K is

$$K = \frac{l}{T^2} = \frac{g}{4\pi^2}\ \text{m/s}^2$$

When the period is 2 seconds, length of the pendulum is about 99.4 cm; this is called a *second's pendulum*. This experiment can also be used to find out the value of 'g' which is a special constant; we shall study about it later.

1.13 Significant Figures

A measurement of 12.4 cm made with a metre scale is accurate to the nearest of a millimetre or 1/10th of a cm. This is not absolutely correct. The accurate value may lie between 12.35 cm and 12.45 cm. In the measurement of 12.4 cm, the figures 1 and 2 are absolutely correct while 4 is reasonably correct. The measurement is said to be accurate upto 3 significant figures.

The same measurement is now made with a more accurate instrument, e.g. a vernier scale and is found to be, say, 12.38 cm. Again the accurate value may lie between 12.375 cm and 12.385 cm. In this measurement 1, 2 and 3 are absolutely correct while 8 is reasonably correct. This measurement is said to be accurate upto 4 significant figures.

Significant figures *is a statement which gives the number of digits upto which we are sure about their accuracy.* In other words, significant figures give the degree of accuracy or precision made with the instrument.

While determining the number of significant figures, we ignore the position of the decimal and count the number of digits involved. The zeros preceding the first digit are not counted. The statement of 3.25 m or 0.0325 km involves 3 significant figures and the measurement is said to have been made upto 3 s.f., whether it is in metres or kilometres.

1.14 Powers of Ten

While speaking of distances, time, mass, etc. we come across numbers which are very large or very small. For example, the nearest star is 37,840,000,000,000,000 m away from us; the time taken by a ray of light to pass through a window pane is 0.000,000,000,003 second. Such numbers are difficult to handle and comprehend. We have also seen earlier that there is not much sense in writing numbers to any significant figures greater than the accuracy in measurement. These problems are simplified by writing very large and very small numbers in short form by expressing them as powers of ten.

For example, the distance of the nearest star can be written as 3784×10^{13} m or 3.784×10^{16} m. If we approximate the distance to two significant figures and write it as 3.8×10^{16} m, this introduces an error of 0.016×10^{16} m in 3.784×10^{16} m which is less than 0.5 per cent.

Similarly, the electric charge on an electron is 0.000,000,000,000,000,000,160 coulomb and its mass is 0.000,000,000,000,000,000,000,000,000,000,911 kg. In powers of ten these can be written as 1.60×10^{-19} coulomb and 9.11×10^{-31} kg, respectively.

1.15 Order of Magnitude

When measurements of quantities are approximated to one significant figure to the left of a decimal, the power of ten is called the order of magnitude.

For example, the distance of the nearest star, 3.8×10^{16} m, has an order of magnitude of 10^{16} m while the distance of the Earth from the Sun, 1.5×10^{11} m, has an order of magnitude of 10^{11} m. These magnitudes indicate that the nearest star is roughly 10^5 times as far away from the Earth as the distance of the Sun from the Earth.

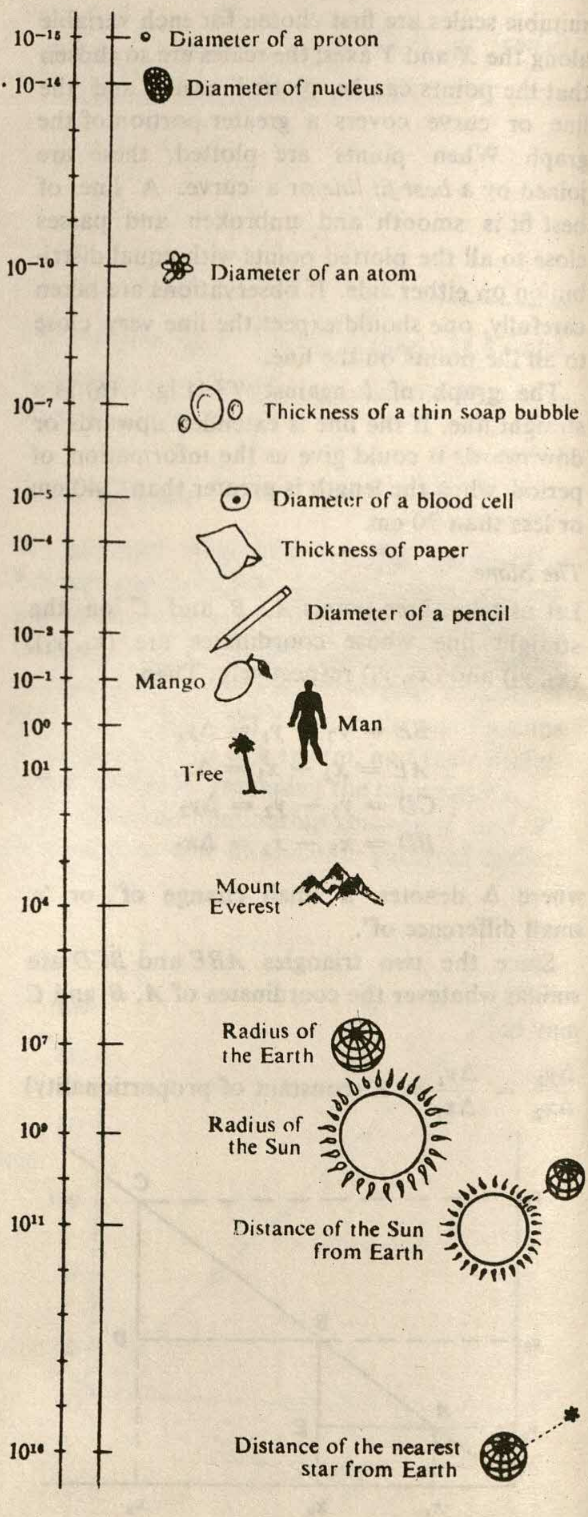


Fig. 1.18

Comparison of size, mass, temperature, time, etc. are easily made and conceived by expressing measurements in order of magnitude. Fig. 1.18 gives the range of distances from our own size to very large and small distances. By employing various techniques and instruments man has been able to extend his knowledge of the very large (macro) and the very small (micro) world of his experience.

QUESTIONS

1. In everyday use, measuring scales of metal, wood and plastic are employed. Discuss if all of them are equally good. How would you decide, if you are given the choice of scales, which is a good scale for measurement?

2. Three measuring jars of capacity 50 ml, 100 ml and 200 ml are available to you. They all have 50 divisions on them and are equally tall.

(a) What is the least count of each measuring jar?

(b) Which of the jars would you use to find out the volume of a liquid which is about 40 ml? Explain.

3. A brick is 25 cm long, 10 cm wide and 6 cm thick. Calculate:

(a) the area of the smallest face; (b) the area of the largest face; and (c) the total area of all its faces.

4. A straight line 12 cm long is moved to a new position parallel to it and 6 cm from the previous position. What is the area of the surface that is swept out in moving the line?

Roll a pencil over a graph paper and use this method to find the area of the pencil.

5. Tie the ends of a thread together to form a closed loop of 20 cm length of the thread. Now spread this thread on a graph paper to make the following shapes: (a) a square of side 5 cm; (b) a rectangle of length 6 cm; (c) a rectangle of length 7 cm; and (d) a circle.

Hence, find the area of each shape. Which of these shapes has the maximum area and which has the least area?

6. A swimming pool is 8 m long, 5 m wide and 2 m deep. When half full, what is the volume of water it contains in (a) m^3 (b) litres. When 20 boys take a dip together in the pool the water level rises by 9 cm. Calculate the average volume of a boy.

7. Describe how you would set up and use a beam balance to determine the mass of an object. What is meant by the mass of an object?

8. The mass of hydrogen atom is approximately 1.7×10^{-27} kg; if the atom is supposed to be cubical in shape of side 1.0×10^{-10} m, calculate the density of the atom.

9. The volume of the Earth is approximately 1.1×10^{21} m^3. If the density of the Earth is assumed to be 5.5×10^3 kg/m^3, calculate the mass of the Earth.

10. An iron girder is 5 m long, 25 cm wide and 20 cm thick. Find its mass, taking the density of iron to be 7.8 g/cm^3.

11. A window pane is 1 metre square and 3 mm thick. Find its mass, if density of glass is 2.5 g/cm^3.

12. By calculation, complete the following table:

Density	*Volume*	*Mass*
8.9 g/cm^3	25 cm^3	— g
2.5 g/cm^3	— cm^3	100 g
— g/cm^3	20 cm^3	210 g
0.09 kg/m^3	25 m^3	— kg

13. How would you expect the density of milk to change if (a) cream was removed from it, (b) water was added to it?

14. A piece of metal has a mass of 113 g and is put into a measuring jar containing water. Calculate the density of the metal if the initial reading is 70 cm^3 and the second reading is 80 cm^3. Which metal is this?

15. From the following data, find the density of turpentine oil:

Mass of empty beaker	=	205 g
Burette reading before running oil	=	1.5 cm^3
Burette reading after running oil	=	26.5 cm^3
Mass of beaker+turpentine oil	=	227 g

16. An empty density bottle weighs 20.2 g and when filled with water it weighs 45.2 g. It weighs 40.2 g when filled with kerosene oil. Find (a) the capacity of the bottle; (b) the density of kerosene oil; (c) the mass of 1 cm^3 of kerosene oil.

17. Name two repetitive phenomena occuring in nature. Which repetitive phenomena exist in the human body?

What is the difference between a repetitive and a periodic phenomena?

18. What is meant by the time period of a vibrating object? What idea does the amplitude of a vibration convey? Explain with the help of a diagram.

19. State whether the time period of a pendulum depends upon the following factors, and if yes, how? (a) mass of the bob; (b) length of the pendulum; (c) amplitude of its oscillation; (d) the factor 'g'.

A simple pendulum of length 1.0 m has a period of 2.0 seconds. What would be the period of a simple pendulum of length (a) 0.5 m; (b) 2.0 m; (c) 4.0 m? What is meant by a second's pendulum?

20. If the bob of a simple pendulum takes 0.5 second to swing from one extreme position to the other extreme position:

(i) Explain the term time period, and find the time period of the pendulum.

(ii) What is meant by the term amplitude? State whether the time period increases, decreases or remains the same when amplitude is increased and mass of the bob is doubled.

(iii) What do you mean by the length of the pendulum? If in the above case the length of the pendulum is increased four times, what will be its time period? What special name is given to such a pendulum? What is its approximate length?

21. A simple pendulum of length 25 cm has a time period of 1 second. Calculate the time period if the length is altered to (a) 50 cm and (b) 1 m.

22. Draw a neat diagram of the apparatus with which you can measure the internal and external diameters of a hollow cylinder.

23. Name the instruments you would use to measure the follwing:

(a) the external diameter of a tube of about 3 cm bore.

(b) the diameter of a wire.

(c) the thickness of a sheet of paper.

24. What do you mean by the pitch and least count of a micrometer screw-guage? Illustrate your answer with labelled diagrams.

A screw-guage has 20 threads in 1 cm and its circular scale has 50 divisions. Work out its pitch and least count.

25. What do you mean by the zero error of a micrometer screw-guage? When is it positive? Illustrate your answer with a diagram.

26. Draw a labelled diagram of a micrometer screw-guage. Mention the precautions you would observe in finding the diameter of a wire with its help.

27. What is the micrometer reading shown in Fig 1.19 in which the horizontal scale has millimetre marks above and half mm marks below the line.

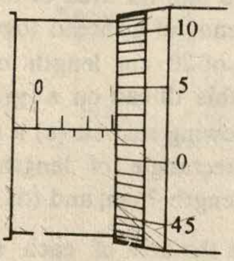


Fig. 1.19

Suppose such a screw guage registers 2.46 mm and the zero error reading is − 0.06 mm What is the corrected reading?

2

Speed and Acceleration

The world is full of things which are in motion; things as small as molecules and as large as planets are moving all the time. We move on the Earth, the Earth rotates about its own axis and revolves round the Sun, and the Sun is moving in our galaxy. Thus, to understand the universe, we must understand motion. There is an old saying: 'To be ignorant of motion is to be ignorant of nature'.

2.1 Motion and Rest

Consider a person at *O* (Fig. 2.1) standing by the roadside who locates a car at the position *A*. After some time he finds the car at the position *B*. This change in position of the car gives the impression to the observer that the car is moving.

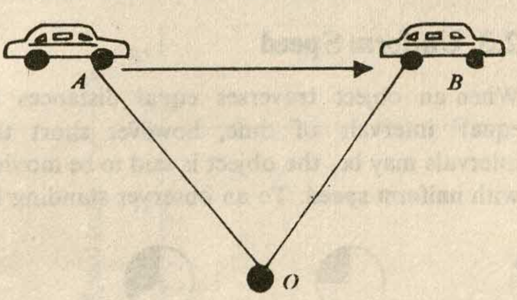


Fig. 2.1

A fellow passenger in the car finds the driver always sitting next to him to his right while the observer at *O* finds the driver changing his position from *A* to *B*. Therefore, we say that the driver is at rest *with respect* to the fellow passenger but is in motion with respect to the observer outside. Thus rest and motion are *relative terms* and are not *absolute*.

An object is said to be in **motion** *if it is changing its position relative to some other object, and is at* **rest** *with respect to some other object if its relative position remains unchanged.* A book lying on a table is at rest with respect to other objects lying near it. To an observer in a skylab, however, all may appear to be in motion. For the sake of simplicity all motions of objects on the Earth are considered with respect to the Earth; the Earth is our fixed *frame of reference* when we talk of motion of objects. When we say that the Sun, stars and the planets rise in the east and set in the west, we consider their motion with respect to the Earth.

2.2 Speed

When you travel in a bus, you enquire how far your destination is and how long it will take to reach the destination These two quantities, distance and time, are related to each other and give you the idea of speed. **Speed** *is the distance covered in unit time, or the rate of change of distance with time.*

$$\text{Speed (m/s)} = \frac{\text{distance travelled (m)}}{\text{time taken (s)}}$$

Speed is measured in cm/s, m/s or km/hour.

If a bus has a speed of 54 km/h it is the same as

$$\frac{54 \times 1000 \text{ m}}{3600 \text{ s}} = 15 \text{ m/s}$$

While travelling in a car you frequently look at the speedometer (Fig. 2.2) which is an instrument used to show the speed of the vehicle at any instant. The speed you notice is the instantaneous speed and is the ratio of the short distance covered in a small time interval.

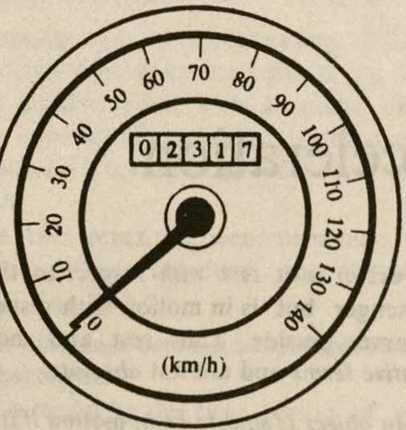


Fig. 2.2

Instantaneous speed

$$= \frac{\text{small change in distance covered}}{\text{time taken in covering the distance}} = \frac{\Delta s}{\Delta t}$$

A bus starting from rest picks up speed and would keep running at the same speed on a straight and clear road; finally the speed decreases as it comes to a stop. If we draw a graph between its speed and time, it would look as shown in Fig. 2.3. In time t_1 the bus has gradually picked up speed which remains steady at 70 km/h from time t_1 to t_2. The speed then gradually reduces to zero from t_2 to t_3.

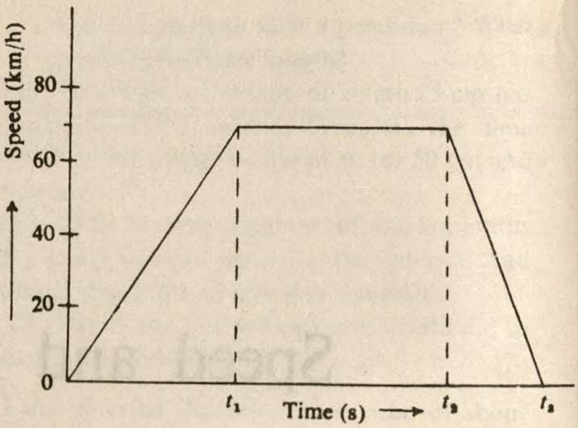


Fig. 2.3

During the total time t_3 from the start, the speed was not 70 km/h all the time, in fact this was the maximum speed attained, and continued for a time $t_2 - t_1$. If you take the ratio of the total distance covered and the corresponding time taken, this is called the **average speed**.

$$\text{Average speed (m/s)} = \frac{\text{total distance covered(m)}}{\text{total time taken (s)}}$$

2.3 Uniform Speed

When an object traverses equal distances in equal intervals of time, however short the intervals may be, the object is said to be moving with **uniform speed.** To an observer standing by

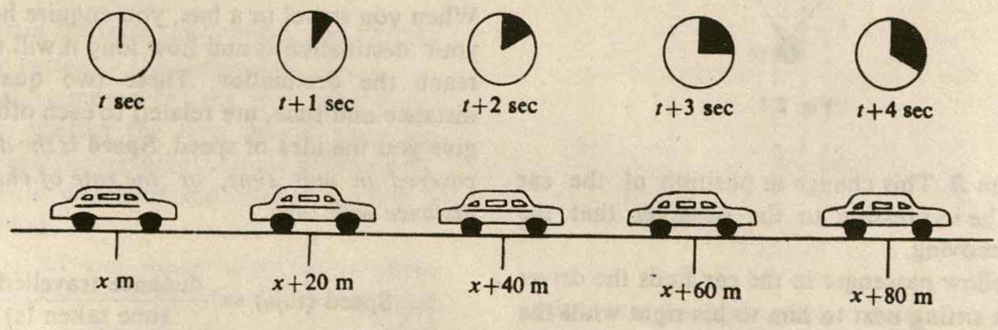


Fig. 2.4

a highway, let a car appear to be at different positions at times as shown in Fig. 2.4.

If you draw a distance-time graph of the car's motion, a straight line is obtained (Fig. 2.5a); the slope of the graph gives its uniform speed:

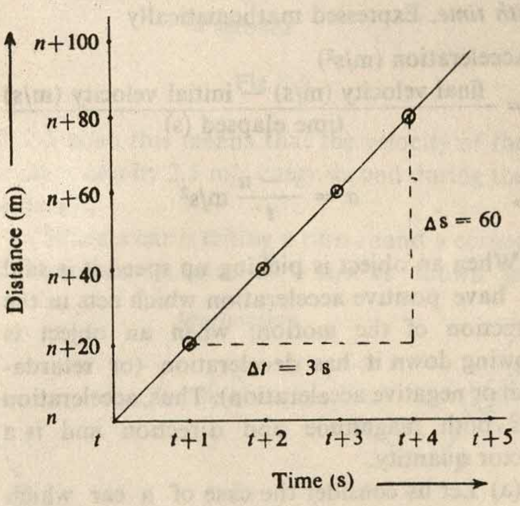


Fig. 2.5(a)

$$\text{Speed} = \text{slope} = \frac{\Delta s}{\Delta t} = \frac{60 \text{ m}}{3 \text{ s}} = 20 \text{ m/s}$$

A graph drawn with the speed and time as the variables, also gives a straight line (Fig. 2.5b) which is parallel to the X-axis, showing that the speed remains constant throughout.

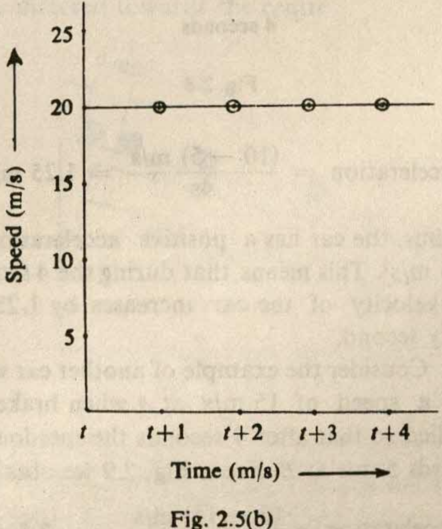


Fig. 2.5(b)

In practice, a bus or a car seldom travels with uniform speed due to uneven roads, turnings and traffic obstacles. Perhaps the speed of a ship in mid-sea and of a long distance train between the outer signals is more or less uniform.

2.4 Displacement

The idea of displacement includes not only a distance traversed but also the directions in which this distance was covered. Consider the example of a snail which starts from position *A* and crawls 40 cm eastwards upto *E*, and then 30 cm northwards upto *N*. How far is the snail now from its starting position?

Fig. 2.6 illustrates the movement of the snail drawn to scale. It will be seen that the final position of the snail is actually 50 cm away from the initial position; this distance is called the displacement.

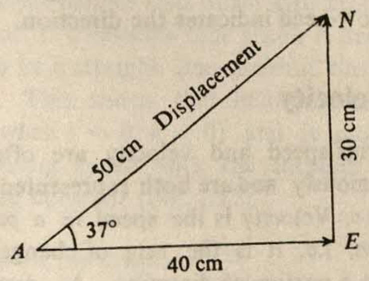


Fig. 2.6

Displacement *is the shortest distance between the initial and the final positions in a specified direction.* In the above case it is 50 cm and its direction is 37° north of east.

Consider another example. A cricket pitch lies east-west and the distance between the two creases is 18 m. A batsman runs from the east crease *A* to the west crease *B* and 15 m on the return journey before he is run out (Fig. 2.7).

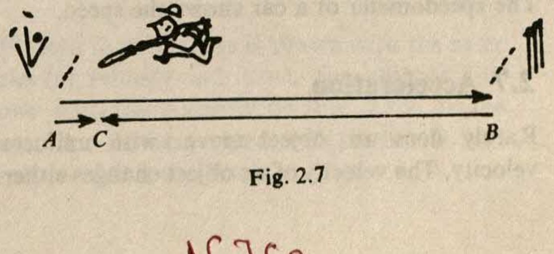


Fig. 2.7

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Then

Displacement $= AC$

$= 3$ m west from A

2.5 Vector and Scalar Quantities

Physical quantities may be classified into two categories.

Scalar *quantities are those which have only magnitude*, i.e. a number and a unit. Examples of scalar physical quantities are length, time, mass, density, focal length and temperature.

Vector *quantities are those which have both direction and magnitude.* Examples of vector physical quantities are force, displacement and weight. A vector can be represented by a straight line with an arrow-head; the length of the line segment represents the magnitude and the arrow-head indicates the direction.

2.6 Velocity

The terms speed and velocity are often used synonymously and are both represented by the symbol v. Velocity is the speed *in a particular direction*, i.e. it is the rate of change of distance in a particular direction. As distance in a particular direction is called displacement, **velocity** *is defined as rate of change of displacement with time.*

$$\text{Velocity} = \frac{\text{change of displacement}}{\text{change of time}}$$

It is measured is m/s or cm/s .

Speed is a scalar quantity and velocity is a vector quantity. In moving along a straight line, speed and velocity are numerically equal. If, however, an object is moving with a uniform speed along a curved path, its velocity is not uniform as the direction changes continuously. Thus speed represents the magnitude of velocity. The speedometer of a car shows the speed.

2.7 Acceleration

Rarely does an object move with uniform velocity. The velocity of an object changes either by increase or decrease of speed, or by a change of direction or when both direction and speed change. Whenever the velocity of an object changes it is said to have acceleration. **Acceleration** *is defined as the rate of change of velocity with time.* Expressed mathematically

$$\text{Acceleration (m/s}^2) = \frac{\text{final velocity (m/s)} - \text{initial velocity (m/s)}}{\text{time elapsed (s)}}$$

or, $$a = \frac{v - u}{t} \text{ m/s}^2$$

When an object is picking up speed it is said to have positive acceleration which acts in the direction of the motion; when an object is slowing down it has deceleration (or retardation or negative acceleration). Thus, acceleration has both magnitude and direction and is a vector quantity.

(a) Let us consider the case of a car which moves from A to B in 4 seconds and the speedometer reading changes from 5 m/s to 10 m/s (Fig. 2.8). Then,

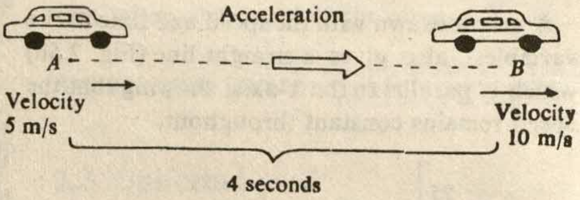


Fig. 2.8

$$\text{Acceleration} = \frac{(10 - 5)\text{ m/s}}{4\text{s}} = 1.25 \text{ m/s}^2$$

Thus, the car has a positive acceleration of 1.25 m/s². This means that during the 4 seconds the velocity of the car increases by 1.25 m/s every second.

(b) Consider the example of another car which has a speed of 15 m/s at A when brakes are applied so that after 4 seconds the speedometer records 5 m/s at B. From Fig. 2.9 we obtain

$$\text{Acceleration} = \frac{(5 - 15)\text{ m/s}}{4\text{s}} = -2.5 \text{ m/s}^2$$

In this case the car has a negative acceleration

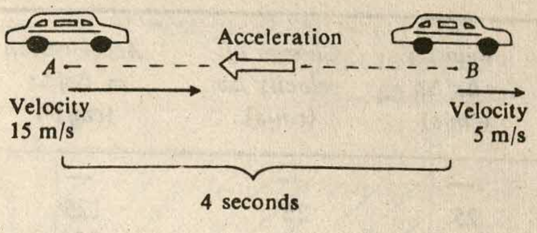


Fig. 2.9

of 2.5 m/s^2; this means that the velocity of the car decreases by 2.5 m/s every second during the 4 seconds.

(c) When a car is taking a turn round a corner and maintains its speed of 5 m/s, as shown in Fig. 2.10, the car's velocity is still considered to change and an acceleration is taking place which is directed towards the centre.

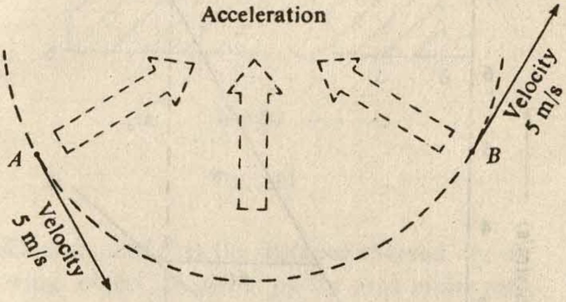


Fig. 2.10

2.8 Uniformly Accelerated Motion

When the velocity of an object changes by an equal amount in equal intervals of time, however small the interval of time may be, the object is said to have uniform acceleration.

A smooth wooden plank is kept slightly inclined to the floor and a big marble is released from its upper edge. It is observed that the marble gathers speed as it rolls down (see Fig. 2.11). In order to measure its velocity and thereby the acceleration at different times, the marble can be photographed after every one-fifth of a second on the same film. The table on P. 24 gives the measurements made on the basis of the experiment.

It is evident that in every successive short interval of 0.2 s, the change in velocity is the same; hence the marble rolls down with uniform acceleration. If a velocity-time graph is drawn, it is seen to be a straight line passing through the origin. This shows that the object started from rest (when $t = 0$, $v = 0$) and is moving with increasing speed with the increase per second being constant (Fig. 2.12).

$$\text{The slope of the graph} = \frac{\Delta v}{\Delta t}$$

$$= \frac{(125 - 25)\ \text{cm/s}}{(1 - 0.2)\ \text{s}} = \frac{100\ \text{cm/s}}{0.8\ \text{s}}$$

$$= 125\ \text{cm/s}^2$$

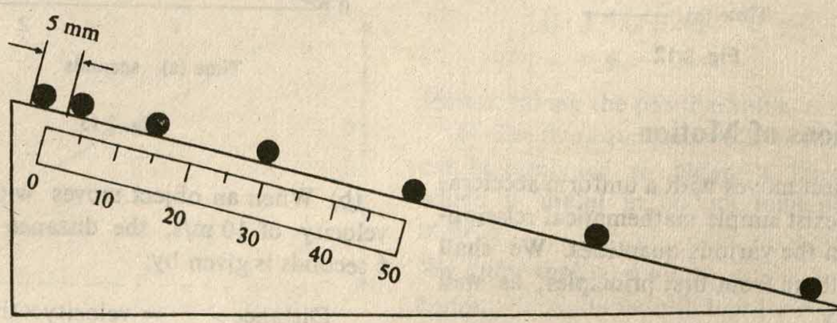


Fig. 2.11

From these examples, it is obvious that the direction of the acceleration may not necessarily be the same as that of the velocity. Does an object moving along a straight line with a uniform velocity possess any acceleration?

If more than one line is drawn with the same scales for velocity and time, the steeper line shows a greater acceleration (Fig. 2.13). In the figure, line *A* has a greater slope than *B*, and the slope of *C* is the least.

Time t (s)	Distance covered s (cm)	Change of distance Δs (cm)	Change of time Δt (s)	Velocity $\Delta s/\Delta t$ (cm/s)	Change of velocity Δv (cm/s)	Acceleration $= \Delta v/\Delta t$ (cm/s^2)
0.0	—	—	—	—	—	—
0.2	5	5	0.2	25	25	125
0.4	15	10	0.2	50	25	125
0.6	30	15	0.2	75	25	125
0.8	50	20	0.2	100	25	125
1.0	75	25	0.2	125	25	125
1.2	105	30	0.2	150	25	125

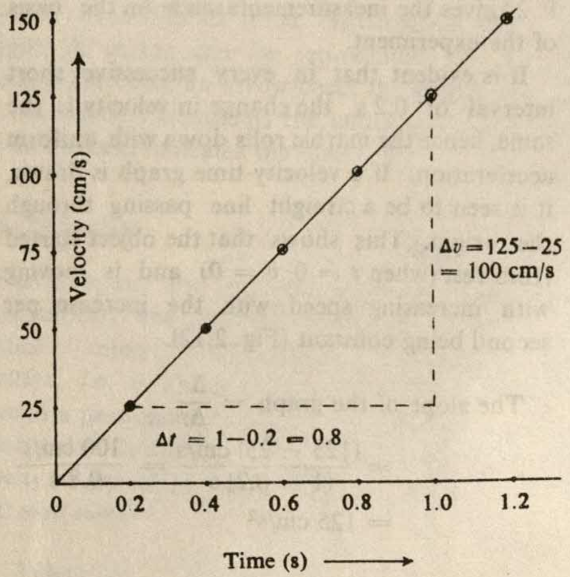


Fig. 2.12

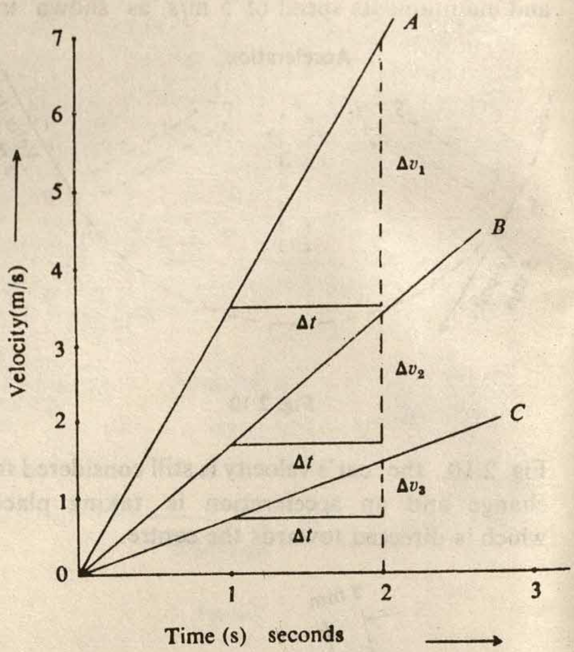


Fig. 2.13

2.9 Equations of Motion

When an object moves with a uniform acceleration, there exist simple mathematical relationships between the various quantities. We shall now derive these from first principles, as well as graphically.

(a) Consider an object which has an initial velocity u; in a time t the velocity changes to v. Then,

$$\text{Acceleration, } a = \frac{v-u}{t}$$

$$\text{hence} \quad v = u+at \qquad \text{(i)}$$

(b) When an object moves with a uniform velocity of 10 m/s, the distance covered s in 6 seconds is given by:

$$\text{Distance} = \text{velocity} \times \text{time}$$
$$= 10 \text{ m/s} \times 6 \text{ s} = 60 \text{ m}$$

If this information is plotted on a velocity-time graph, we obtain a straight line AB parallel to the time axis (Fig. 2.14). On this graph

$OA = 10$ m/s

and $OC = 6$ s

Hence, area of rectangle $OABC = OA \times OC$

$$= 10 \text{ m/s} \times 6 \text{ s}$$

$$= 60 \text{ m}$$

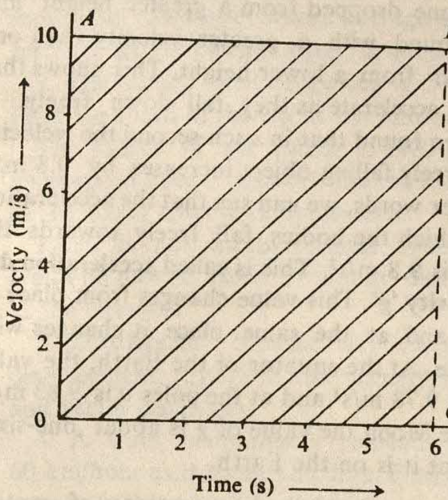


Fig. 2.14

Thus we find that the distance covered by a moving object is given by the area under the velocity-time graph when expressed in proper units. Fig. 2.15 gives the velocity-time graph of the uniformly accelerated motion. The initial velocity at time $t = 0$ is u m/s and the final velocity at time t is v m/s. In this case,

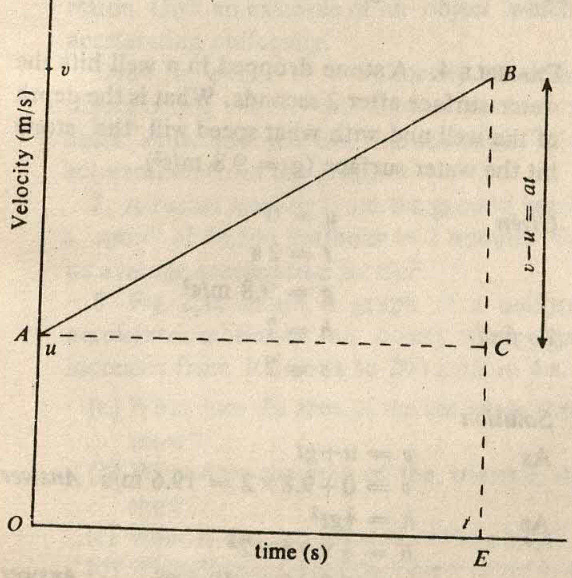


Fig. 2.15

Distance covered in t seconds

$$= \text{area of trapezium } OABE$$

$$= \text{area of rectangle } OACE + \text{area of triangle } ABC$$

$$= OA \times OE + \tfrac{1}{2} BC \times AC$$

$$= u \times t + \tfrac{1}{2} at \times t$$

Hence, $s = ut + \frac{1}{2}at^2$ (ii)

Example 1 An object moving with a velocity of 200 cm/s accelerates at the rate of 10 cm/s^2 for 3 seconds. Calculate the distance covered during this time.

Given $u = 200$ cm/s

$a = 10$ cm/s^2

$t = 3$ s

To find $s = ?$

Solution

$$s = ut + \tfrac{1}{2}at^2$$

$$= 200 \times 3 + \tfrac{1}{2} \times 10 \times 3 \times 3 = 600 + 45$$

$$= 645 \text{ cm}$$

$$= 6.45 \text{ m}$$

Answer

Example 2. An object with an initial velocity of 50 cm/s has an acceleration of 5 cm/s^2. In how much time will it cover 240 cm ?

As $s = ut + \frac{1}{2}at^2$

$\therefore$ $240 = 50t + \frac{1}{2} \times 5 \times t^2$

Hence, $480 = 100t + 5t^2$

or $t^2 + 20t - 96 = 0$

or $(t - 4)(t + 24) = 0$

$\therefore$ $t = 4, -24$

Hence, taking the positive value, $t = 4$ seconds

(c) The two equations we have derived earlier can be combined to obtain a third equation which is useful in solving some problems on motion.

We know that $v = u + at$ (i)

hence, $v^2 = u^2 + 2uat + a^2t^2$

or $v^2 - u^2 = 2a(ut + \frac{1}{2}at^2)$

$= 2as$ from (ii)

$\therefore$ $v^2 - u^2 = 2as$ (iii)

Example 3. A car moving with an initial speed of 40 m/s on applying the brakes comes to rest after travelling 8 m. Find the acceleration.

As $v^2 - u^2 = 2as$

$\therefore$ $a = \dfrac{v^2 - u^2}{2s}$

or $a = \dfrac{0 - 40^2}{2 \times 8} = \dfrac{-1600}{16}$

$= -100 \text{ m/s}^2$

Hence acceleration $a = -100 \text{ m/s}^2$

or deceleration $= 100 \text{ m/s}^2$ *Answer*

The three equations of motion are very useful in solving problems on motion of objects which are travelling with constant acceleration.

2.10 The Free Fall

It is a common experience that if you hold a stone in one hand and a piece of paper in the other hand, and release both of them simultaneously from the same height, the stone falls down quickly and hits the ground earlier than the paper. This notion that heavy objects fall down faster than the lighter ones persisted for a long time. Perhaps in the early 16th century Galileo was the first person to show that if the resistance of air is eliminated, objects reach the ground at the same time when they are released simultaneously from the same height.

Activity 1. Cut a piece of paper of the same size as that of the 50 paise coin. Release them simultaneously from the same height; the paper falls slower than the coin. Now eliminate the resistance of air by placing the piece of paper on the coin and then release the combination from a certain height. The two are found to fall together. The coin shields the paper from the resistance of air and they fall together.

Robert Boyle removed air from a tall jar which contained a coin and a feather. On inverting the jar he found that both the feather and the coin reach the bottom of the jar at the same time.

In 1971, astronaut R. Scott released a hammer from one hand and a feather from the other on the Moon and observed that both fall together. This is because the Moon has no atmosphere, and consequently there is no resistance of air. It was a simple, yet an exciting experiment in physics to show the absence of atmosphere on the Moon.

A stone dropped from a greater height hits the ground with a greater velocity than one dropped from a lower height. This shows that objects accelerate as they fall down freely. It has been found that in each second the velocity of a freely falling object increases by 9.8 m/s. In other words, we can say that the acceleration with which the bodies fall freely towards the Earth is 9.8 m/s^2. This is called **acceleration due to gravity '*g*'**. This value changes from place to place and at the same place it changes with altitude. At the equator of the Earth, the value of g is 9.78 m/s^2 and at the poles it is 9.83 m/s^2. On the Moon the value of g is about one-sixth of what it is on the Earth.

During a free fall, the equations of motion become as follows:

$v = u + gt$

or $v = gt$ when the body falls from rest

$h = ut + \frac{1}{2}gt^2$

$= \frac{1}{2}gt^2$ when the body falls from rest

$v^2 - u^2 = 2gh$

or $v^2 = 2gh$ when the body falls from rest

EXAMPLE 4. A stone dropped in a well hits the water surface after 2 seconds. What is the depth of the well and with what speed will the stone hit the water surface ($g = 9.8 \text{ m/s}^2$).

Given $u = 0$

$t = 2 \text{ s}$

$g = 9.8 \text{ m/s}^2$

To find $h = ?$

$v = ?$

Solution

As $v = u + gt$

$\therefore$ $v = 0 + 9.8 \times 2 = 19.6 \text{ m/s}$ *Answer*

As $h = \frac{1}{2}gt^2$

$\therefore$ $h = \frac{1}{2} \times 9.8 \times 2^2$

$= 9.8 \times 2 = 19.6 \text{ m}$ *Answer*

QUESTIONS

1. A car is running at a speed of 72 km/hour; find its speed in m/s. Give an example of the motion of an object whose average velocity is zero but whose average speed is not zero.

2. The minute hand of a clock is 7 cm long. Find the speed of the tip of the minute hand?

The radius of the Earth is 6400 km. With what speed does a man on the equator move as the Earth rotates round its axis?

Delhi is not on the equator. Will a man at Delhi be moving faster or slower than a man at the equator?

3. Distinguish between (a) distance and displacement; (b) speed and velocity; (c) scalar and vector quantities.

4. A train maintains a constant speed of 60 km/hour as it rounds a curve. Find the speed in m/s. Is the velocity constant?

A car travels south for 5 km and then 30° east of south for 5 km. Find the resultant displacement by drawing a diagram.

5. Is acceleration a vector or a scalar quantity? Explain. Why does the unit of acceleration involve the unit of time twice?

What does the speedometer of a car tell you? How does it work?

6. Define (a) acceleration, (b) uniform acceleration. Give an example of an object which is accelerating uniformly.

Draw a graph of a uniformly accelerated object taking velocity and time as the two variables; show how you can find the value of the acceleration from the graph.

7. A rocket starting from the ground reaches a speed of 34,560 km/hour in 2 minutes. Find its average acceleration in m/s^2.

8. Fig. 2.16 shows a graph of a uniformly accelerated motion of an object whose speed increases from 100 cm/s to 200 cm/s in 4 s.

(a) What does the area of the rectangle *OACD* show?

(b) What does the area of the triangle *ABC* show?

(c) What is the acceleration of the object?

(d) What distance does the object cover in 4 s?

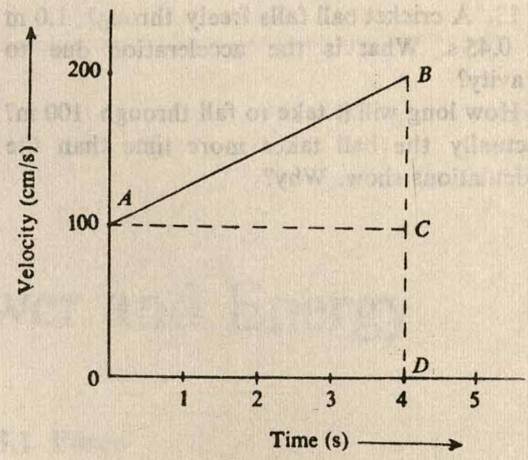


Fig. 2.16

9. A trolley running down an inclined plane travels distances s in times t as shown in the following table:

s (cm)	0	2.4	9.6	21.6	38.4	60.0	86.4
t (s)	0	0.2	0.4	0.6	0.8	1.0	1.2

Plot a velocity-time graph and use the graph to determine (a) the acceleration of the trolley; (b) the distance it has moved in 5 seconds after starting from rest.

10. Draw (i) a distance-time graph, (ii) velocity-time graph of an aeroplane flying due east at a constant speed of 500 km/hour. How can the value of the speed be obtained from the distance-time graph?

11. A car starts from rest on a level road with a uniform acceleration of 2 m/s^2 till it attains a speed of 10 m/s; the car continues with this speed for another 10 seconds. It is then brought to rest with a uniform retardation in 2 seconds. Draw a speed-time graph of the car's motion.

Find the total distance covered by the car during its motion (a) from the graph; (b) by calculation using the equations of motion.

12. Explain the term acceleration due to gravity. How would you find its value when a

small object is allowed to fall freely to the ground?

13. A cricket ball falls freely through 1.0 m in 0.45 s. What is the acceleration due to gravity?

How long will it take to fall through 100 m? Actually the ball takes more time than the calculations show. Why?

14. Is it possible for an object to be accelerated without its speed changing? If so, how?

15. Sketch a graph showing the relation between time and distance travelled by an object falling freely from rest. How would you use the graph to determine (a) the velocity of the object at any instant; (b) the acceleration due to gravity?

3

Force, Work, Power and Energy

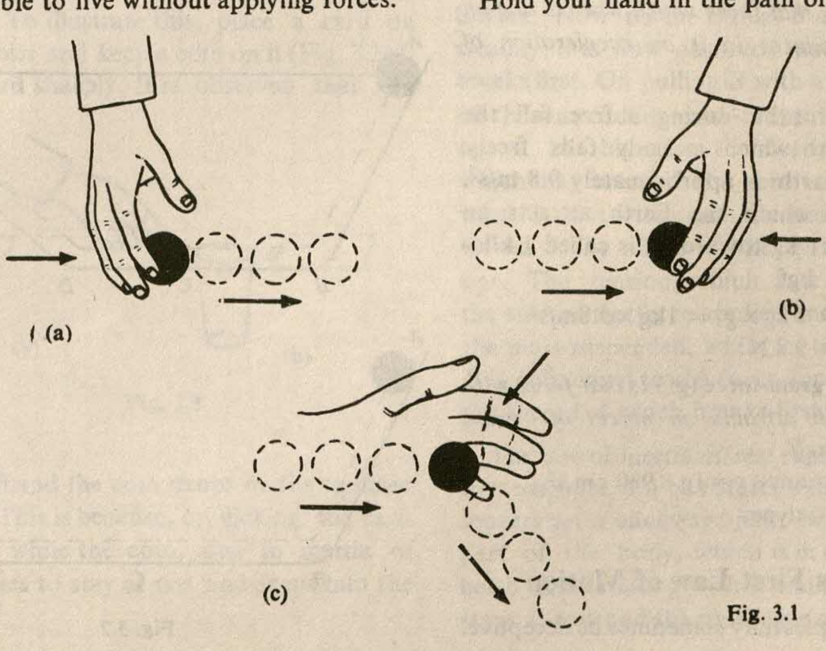
The use of force in our daily life is as common as breathing. On kicking or throwing a ball up, you apply *muscular* force on it and it comes down due to another force called *gravitational* pull. A ball rolling on the ground slows down and comes to rest by a force known as *friction.* A batsman while hitting a ball not only makes it move faster but also changes its direction by holding the bat at an angle to the direction of motion of the incoming ball. A horse pulls a tonga and people push a car to start it, if the self-starter is not working. If you want to move a lawn-mower you either push or pull it. It is in fact impossible to live without applying forces.

3.1 Force

Force is usually in the form of a **push** or **pull**. This, however, conveys nothing as push and pull are just the synonyms of force. In order to have an operational definition of force, it is desired to know the effects which force produces on acting upon bodies.

Activity 1. Push a ball along a floor; it starts rolling (Fig. 3.1a). Hold your hand in the path of the rolling ball and apply a push opposite to the direction of motion. The rolling ball slows down and ultimately comes to rest, see Fig. 3.1b.

Hold your hand in the path of a rolling ball,


(a)

(b)

(c)

Fig. 3.1

inclined at an angle to its direction of motion (Fig. 3.1c). The direction of motion of the ball changes after it hits the hand. The shape of the ball may change if it is squeezed between two hands. Hence **force** is *a push or pull which changes or tends to change the state of rest or uniform motion of a body along a straight line; it may also change the size or shape of a body.*

It can be proved that force is equal to the product of mass of the body on which it acts and the acceleration produced thereby in it Mathematically

$$\text{Force} = \text{mass} \times \text{acceleration}$$

or

$$F = ma$$

Unit of Force

In the MKS system of units which we are using throughout in this book, the unit of force is *newton*. From the equation $F = ma$, we see that

if $m = 1$ kg; $a = 1 \text{m/s}^2$ then F should be 1

i.e., 1 newton $= 1 \text{ kg} \times 1 \text{m/s}^2$

Thus 1 **newton is** *that force which when acts on an object of* 1 *kg mass produces in it an acceleration of* 1 *m/s*^{2}.

If $m = 1$g; $a = 1 \text{cm/s}^2$ then F is 1 dyne

i.e. 1 dyne $= 1\text{g} \times 1 \text{cm/s}^2$

Thus one **dyne** *is that force which when acting on 1 gram mass produces in it an acceleration of 1 cm/s*^{2}.

You have learnt that during a free fall the acceleration with which a body falls freely towards the Earth is approximately 9.8 m/s^2. The force with which the Earth attracts an object of mass 1 kg towards it is called **1 kilogram force** or 1 kgf.

$$1 \text{ kgf} = 1 \text{ kg} \times g = 1 \text{kg} \times 9.8 \text{m/s}^2$$
$$= 9.8 \text{ N}$$

Similarly one **gram-force** (gf) *is that force with which the Earth attracts an object of 1 gram mass towards itself.*

$$1 \text{ gf} = 1 \text{ gram} \times g = 1\text{g} \times 980 \text{ cm/s}^2$$
$$= 980 \text{ dynes}$$

3.2 Newton's First Law of Motion

Everyday examples may sometimes be deceptive. If a cyclist stops pedalling, the cycle soon comes to a stop. To keep a book moving with uniform speed on a table, you must apply a force on it all the time. Such common experiences led the great Greek philospher Aristotle to state that 'a force is needed to keep objects moving; in the absence of a force they will come to rest'. Galileo was the first scientist who, on the basis of his experiments and logical thinking, questioned Aristotle's statement. Fig. 3.2 shows more or less the same arrangement as used by Galileo.

Two inclined planes *ABC* and *EDC* are kept facing each other in such a way that the ball rolling down *ABC* goes up *CDE*. The angle of inclination of the plane *EDC* can be changed (Fig. 3.2).

On rolling a ball down *ABC*, it is observed that the ball climbs up the second plane to

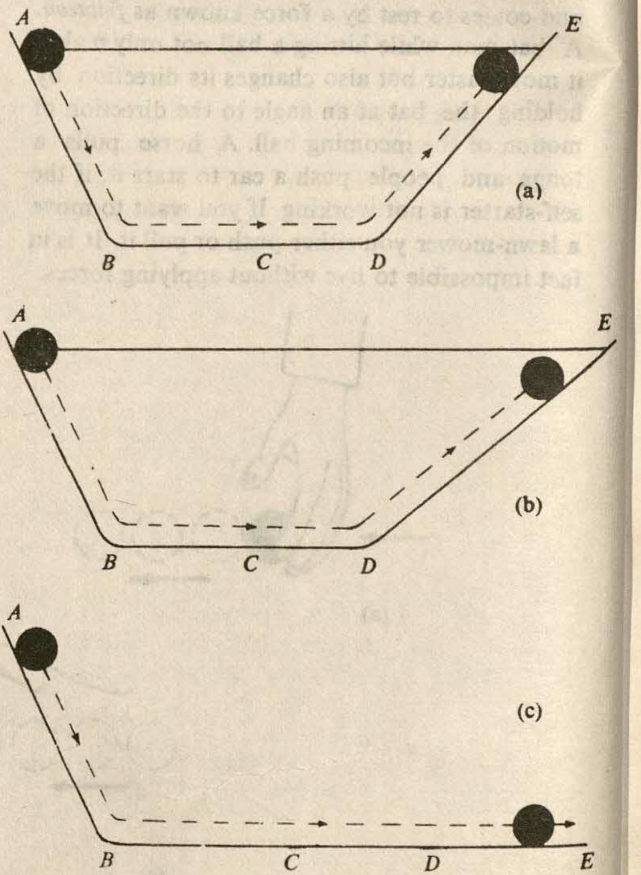


Fig. 3.2

almost the same height. Because of friction it is unable to climb exactly up to the same height. On decreasing the slope of the second plane, it is observed that the ball almost rises again to the same height even though it has travelled a greater distance.

Galileo believed that if friction were removed and the second plane is made horizontal (Fig. 3.2c), then in the quest to rise to the same height, the ball will keep rolling on and on. In actual practice the ball comes to rest due to friction.

From this we infer that 'no force is needed to keep an object moving'. Issac Newton put the ideas of Galileo in the form of a law called the *First Law of Motion* which states that *every object continues in its state of rest or of uniform motion along a straight line unless an unbalanced force acts on it.*

This law is also called the Law of Inertia. Inertia *is the tendency of an object to stay at rest or to resist change in its motion.* The law can be divided into two parts:

(a) *Law of inertia of rest* which states that every object continues in its state of rest *unless an unbalanced force acts on it.*

Activity 2. To illustrate this, place a card on a glass tumbler and keep a coin on it (Fig. 3.3a) Flick the card sharply. It is observed that the card flies off and the coin drops in the tumbler (Fig. 3.3b). This is because, on flicking, the card moves away while the coin, due to inertia of rest, continues to stay at rest and drops into the tumbler.

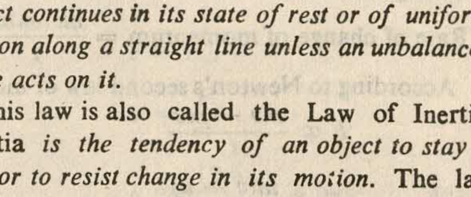


Fig. 3.3

Activity 3. Suspend a heavy mass from a rigid support using a fine thread *A*. Tie a piece of similar thread *B* to the base of the mass (Fig. 3.4).

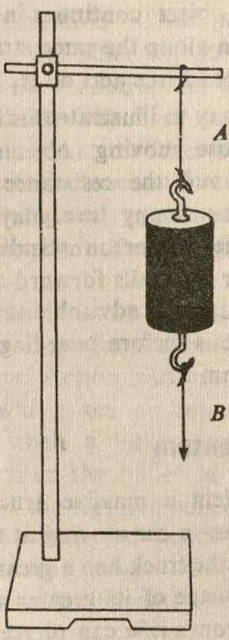


Fig. 3.4

Pull the thread *B* with a jerk; the thread *B* breaks. Now tie the thread *B* again and pull it steadily; it is now observed that the thread *A* breaks first. On pulling *B* with a jerk, the inertia of the suspended mass resists the force to act on *A*. In this case the force only acts on *B* which may break if the tension is more than what it can withstand. On steadily pulling the thread *B*, the whole of the system behaves as one. The tension which acts on *A* is equal to the sum of the force applied and the weight of the mass suspended, while the tension acting on *B* is only equal to the force applied. Thus it is the thread *A* which breaks first.

The law of inertia of rest explains many facts. For example, if a bus starts suddenly the passengers get a backward jerk, because the lower part of the body, which is in contact with the berth, moves along with it while the upper part stays at rest and the passenger gets a backward jerk. Similarly on beating a suspended carpet or *durrey*, the carpet moves ahead with a jerk, while dust particles stay at rest and fall down.

(b) *Law of inertia of motion* which states that every object continues in its state of uniform motion along the same straight line unless an unbalanced force acts on it.

It is not easy to illustrate this law with experiments because moving objects get retarded by friction and the resistance of air. The law also explains many everyday observations. For example, a person standing on a moving bus bends or even falls forward as the bus stops suddenly. Also it is advisable to run along with a moving bus before boarding it or even after alighting from it.

3.3 Momentum

In an accident a massive truck causes more damage than a car moving at the same speed. We say that the truck has a greater 'quantity of motion' by virtue of its greater mass. A small bullet fired from a rifle can pierce through a tree trunk while a pebble of equal mass flung on it does little damage. We explain this by saying that the bullet possesses a greater quantity of motion because of its high speed. Newton used the word 'momentum' for the quantity of motion possessed by an object. *Momentum is the product of mass of an object and its velocity.*

$$\text{Momentum (kg m/s)} = \text{mass (kg)} \times \text{velocity (m/s)} = mv$$

Momentum is a vector quantity and has the same direction as that of velocity.

3.4 Newton's Second Law of Motion

When a force is applied on a moving object, it moves faster or slows down depending on the direction in which the force is applied. In other words, the momentum changes by the application of the force. The direction of force and the direction in which the momentum changes are the same.

The barrel of a long range rifle is longer so that the force acting on the bullet lasts for a longer duration. This greatly increases the velocity of the bullet, and hence its momentum, as it leaves the barrel. Thus, greater the duration of the force applied, greater will be the change of momentum. These two observations were summed up by Newton in the form of the *Second Law of Motion* which states that *the rate of change of momentum is directly proportional to the force applied and acts in the direction of the force.*

Suppose a body of mass m is moving with a velocity u. A force F acts on it for t seconds and changes its velocity to v. Then

$$\begin{aligned}\text{Initial momentum} &= mu\\ \text{Final momentum} &= mv\\ \text{Change of momentum} &= mv - mu\\ \text{Rate of change of momentum} &= \frac{mv - mu}{t}\end{aligned}$$

According to Newton's second law of motion

$$F \propto \frac{mv - mu}{t}$$

or $$F \propto \frac{m(v - u)}{t}$$

or $$F \propto ma \quad \text{as } a = \frac{v - u}{t}$$

or $$F = kma$$

where k is the constant of proportionality. The numerical value of the constant k is made equal to unity by properly defining the unit of force. The second law of motion can be expressed mathematically as

$$F = ma$$

or $$\text{Force} = \text{mass} \times \text{acceleration}$$

It may be noted that the first law gives the definition of force and the second law gives the equation of force. Also it may be noted that the second law incorporates the first law. According to the second law

$$F = ma$$

If no force acts on the body, F will be zero

$$\therefore \quad ma = 0$$

But m can never be zero, therefore $a = 0$. This means that when no unbalanced force acts on a body, acceleration or change of velocity should be zero. This is the case when the body at rest continues to be at rest and the moving body continues to move with uniform speed along a straight line. This is the first law.

EXAMPLE 1. A force of 2 kgf acts on a body of mass 4.9 kg. Find the acceleration produced. How far will the body move in 2 seconds? ($g = 9.8 \text{ m/s}^2$)

Given $F = 2 \text{ kgf} = 2 \times 9.8 \text{ N}$

$= 19.6 \text{ N}$

$m = 4.9 \text{ kg}$

$t = 2 \text{ s}$

To find $a = ?$

$s = ?$

Solution

As $F = ma$

$\therefore \quad a = \dfrac{F}{m}$

or $a = \dfrac{19.6}{4.9} = 4 \text{ m/s}^2$ *Answer*

As $s = ut + \dfrac{1}{2}at^2$

$\therefore \quad s = 0 + \dfrac{1}{2} \times 4 \times 2^2$

$= 8 \text{m}$ *Answer*

3.5 Newton's Third Law of Motion

While firing a rifle it is desirable to keep the butt pressed hard against the shoulder to avoid being hurt. Why? In order to answer this and to even understand the working of jet engines and rockets, it is essential to know Newton's third law of motion in detail.

Activity 4. Attach the hooks of two spring balances together and let two boys gradually pull them apart until one of them reads 10 N (Fig. 3.5). You will observe that the other spring balance also reads 10 N. This shows that while the first boy is pulling the second, the second is also pulling the first with equal force.

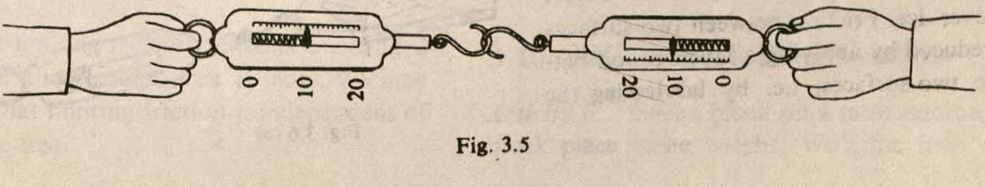


Fig. 3.5

Now let one boy hold the balance steady in his hand while the other boy pulls the second balance. When the second spring balance reads 10N, it is found that the first one also reads 10 N. This shows that the force applied by the second boy created a reaction force which was equal in magnitude and opposite in direction to the force applied. This is the third law of motion.

Newton's third law of motion states that *every action is accompanied by an equal and opposite reaction.* Action and reaction form a pair of forces which act on separate objects. For example, when a bullet is fired by a gun, action force acts on the bullet in the forward direction while the reaction acts on the gun in the opposite direction, and hence the gun recoils. This is the reason why, while firing a rifle, the butt is pressed hard against the shoulder.

In a jet engine, fuel is burnt in the combustion chambers forming a large quantity of hot gases. A high pressure thus develops in the chambers which drives the gases out of the jet. The engine exerts a backward force on the gases; the gases exert an equal and opposite force in the forward direction on the jet engines. The action and reaction are equal in magnitude and opposite in direction and *they act on separate objects.*

3.6 Mass and Weight

Mass is the quantity of matter contained in a body and is measured in kilograms with a beam balance. It is a constant quantity.

Weight is the force with which the Earth pulls a body lying on or near its surface towards its centre. It is measured with a spring balance in kgf or newtons.

If the mass of a body is m, then its weight is mg. Weight varies as g; it is maximum at the poles and minimum at the equator. As we go up from the Earth's surface or down in mines, the weight of an object decreases. The weight of an object on the surface of the Moon is about one-sixth of what it is on the Earth.

3.7 Friction

According to the law of inertia of motion, a moving object should continue moving uniformly along the same straight line. But we observe that a ball rolled on the ground, and a moving automobile whose engines are shut off, slow down and ultimately come to rest. This is due to **friction**. Friction plays an important role in our daily life and is so common that we take it for granted. Whenever one surface moves over another surface, friction invariably comes into play and opposes the motion.

When one surface moves over another surface, the force which opposes the motion or which acts opposite to the direction of motion is called **friction.**

If we observe any surface either with the help of a magnifying glass or under a microscope, we notice that the surface is marked with projections and depressions. When one surface moves over another, these nonuniformities interlock with each other and oppose motion. Molecules of the two surfaces also attract each other and oppose motion. Thus we can say that friction comes into play when one surface moves over another due to the **force of adhesion** (attraction between molecules of two different bodies) and interlocking of the nonuniformities of the two surfaces in contact. Friction is less when the two surfaces are smooth such as when an object moves over ice. Friction between two surfaces can be reduced by applying a layer of oil between the two surfaces, i.e. by **lubricating** the surfaces.

Limiting Friction

Activity 5. Attach a spring balance to a wooden block placed on a flat surface, say a table. Pull the spring balance a little, the block remains stationary. Gradually increase the pull till it begins to move. Let this pull be 200 gf. This means that the block does not move when the pull is 100 gf or 150 gf and begins to move when the pull is increased to 200 gf (Fig. 3.6 a).

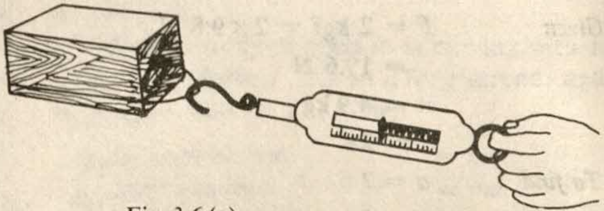


Fig. 3.6 (a)

We may conclude from the above experiment that friction is self adjusting upto a certain maximum limit called **limiting friction**. In other words, **limiting friction** *is the maximum force of friction which comes into play when one surface moves over another and is equal to the force required to just move one surface over another.*

3.8 Laws of Friction

Friction depends upon the following factors.

1 *Normal Reaction*

The force of friction F is directly proportional to to the normal reaction R, i.e.

$$F \propto R$$

In Activity 5, normal reaction is equal to the weight of the block. This is because the block pushes down the table with a force equal to its weight and the table pushes up the block with

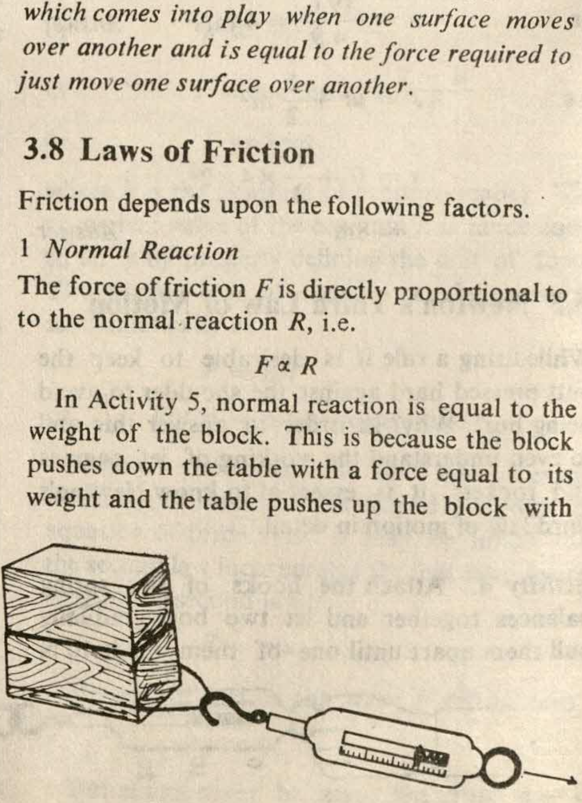


Fig. 3.6 (b)

the same force (Newton's third law of motion). Friction or limiting friction is equal to the force of 200 gf which is required to just move the block.

Now place a similar block on the top of the first as shown in Fig. 3.6 (b) and gradually pull the spring balance such that the two blocks just begin to move. It is found that the limiting friction becomes 400 gf, i.e. double of what it was before. This shows that the limiting friction is doubled when the normal reaction is doubled, or $F \alpha R$

2. *Surface Area*

Repeat the above experiment with one block standing vertically as shown in Fig. 3.6 (c). It is found that the pull required to just move one block remains the same, i.e. equal to 200 gf, even when the surface area is less.

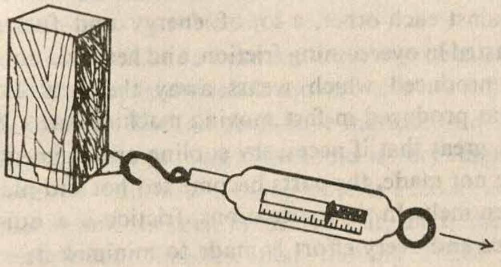


Fig. 3.6 (c)

Repeat the experiment with two blocks as shown in Fig. 3.6 (d). The normal reaction is again found to be 400 gf, as was the case when one block was placed on top of the other. This shows that limiting friction remains unchanged even when the surface area is more. We may conclude that limiting friction is independent of the surface area.

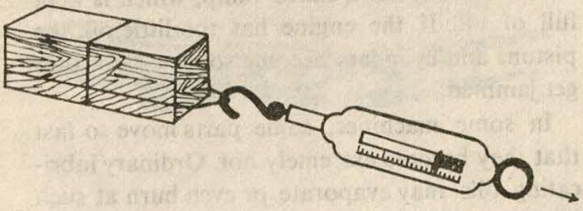


Fig. 3.6 (d)

3. *Nature of the Surface in Contact*

Repeat the experiment with one block wrapped in a piece of paper. It is found that limiting friction decreases. We may conclude that limiting friction depends upon the nature of the two surfaces in contact.

From the first law of fricton we know that limiting friction is directly proportional to the normal reaction, that is

$$F \alpha R \text{ or } F = \mu R$$

where μ is a constant called the **coefficient of friction**. It depends upon the nature and roughness of the two surfaces in contact.

Hence $$\mu = \frac{F}{R}$$

or, $$\text{Coefficient of friction} = \frac{\text{limiting friction}}{\text{normal reaction}}$$

The coefficient of friction for two metal surface varies from 0.15 to 0.30 while that between a metal and leather is 0.6. The high value in the latter case is one of the reasons for using leather belts in machinery.

3.9 Static and Dynamic Friction

Limiting friction is either static or dynamic. **Static friction** is equal to the force required to just move one body over another. **Dynamic friction** is the force which is required to keep moving one body steadily over another. It is found that the force required to just move one body over another is more than the force required to keep the body steadily moving over another. In other-words

Static friction > Dynamic friction

Static friction is larger than dynamic friction because when the two surfaces are at rest interlocking of the inequalities of the two surfaces is more firm than when the surfaces are in motion. It is noticed that dynamic friction is independent of the velocity or speed of motion.

3.10 Sliding and Rolling Friction

Activity 6. Place a block on a table and on the block place some weight. With the help of a

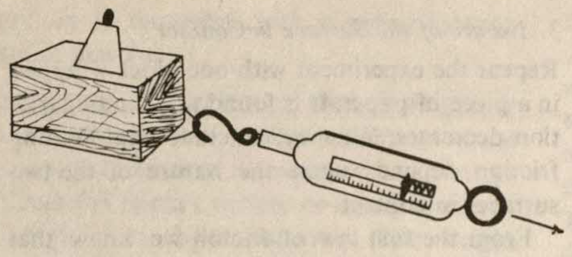


Fig. 3.7 (a)

spring balance find the force required to just slide the combination (Fig. 3.7 a).

Now place some pencils (acting as rollers) or ball bearings under the block and repeat the experiment (Fig. 3.7 b).

It is observed that the pull required to just roll the block is much less than that required to just slide it.

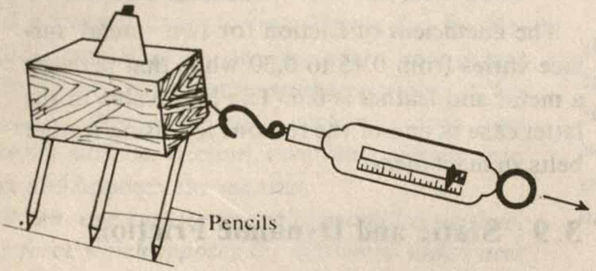


Fig. 3.7 (b)

We may conclude that **rolling friction** is much less than **sliding friction.** This knowledge was used by early man when he invented the wheel. The builders of the pyramids in Egypt used rollers to drag huge stone blocks.

3.11 Advantages of Friction

1. It would be impossible for us to walk if there was no friction. It is on account of friction that we are able to move forward by pushing the ground with our feet. Without friction our feet would slip just as on ice or on a very smooth surface.

2. The movement of automobiles is made possible because of the friction between the tyres and the road surface. The car engine turns the wheels and the rubber tyres on them push backwards against the road. Friction opposes this. and pushes forward on the tyres. The car th moves. The 'tread' on the tyres increases friction. Smooth tyres tend to skid, especially on wet, greasy or icy roads. Sometimes sand is put on roads to increase friction and avoid loosening of the grip of the wheel.

3. Brakes work because of friction. On applying the brakes in an automobile, the brake shoes rub against the rim of the wheel and the friction between them reduces the speed.

4. It is possible to tighten screws, bolts and nuts because of friction. A motor car jack must have a lot of friction to avoid slipping down of the jack when we stop raising it.

3.12 Disadvantages of Friction

Any moving body has to overcome the force of friction. This causes wastage of energy and hence of fuel. When two parts of any machine rub against each other, a lot of energy and fuel is wasted in overcoming friction, and heat and noise is produced which wears away the parts. The heat produced in fast moving machines may be so great that if necessary cooling arrangements are not made, the parts become red hot and may even melt. In these situations, friction is a nuisance and every effort is made to minimise it.

3.13 Ways to Reduce Friction

Friction is decreased by **lubrication** with oil, grease and graphite. Bicycles and machines need oil regularly. The engine of a motorcar has a case at the bottom, called sump, which is kept full of oil. If the engine has too little oil, the pistons and cylinders become so hot that they get jammed.

In some machines, some parts move so fast that they become extremely hot. Ordinary lubricating oils may evaporate or even burn at such high temperatures. In such situations, therefore, graphite is used as a lubricant. Graphite is a soft form of carbon which is very slippery and does not burn at such high temperature.

There is friction between a wheel and its axle. The wheel and axle are separated by steel rollers or **ball bearings**, which roll as the wheel turns. By doing so, instead of having sliding friction between the wheel and axle we have rolling friction which is much less than the former.

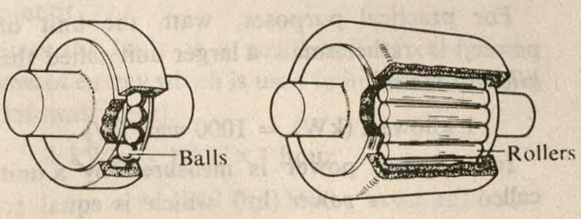


Fig. 3.8

Friction can be decreased by the use of anti-friction materials. It is observed that friction between two bodies of the same metal is much more than between two bodies of two different metals. Hence the inside surface of bearing is lined with an alloy, so that the steel axle rolls over a different metal, and hence the bearing experiences less friction.

There is friction between a moving object and the air through which it moves; this is call **air resistance**. The air resistance increases with the speed of the moving object and is very high in case of very fast moving objects such as aeroplanes and rockets. To decrease it, the bodies of aeroplanes, missiles, fast moving trains and space ships are streamlined (Fig 3.9).

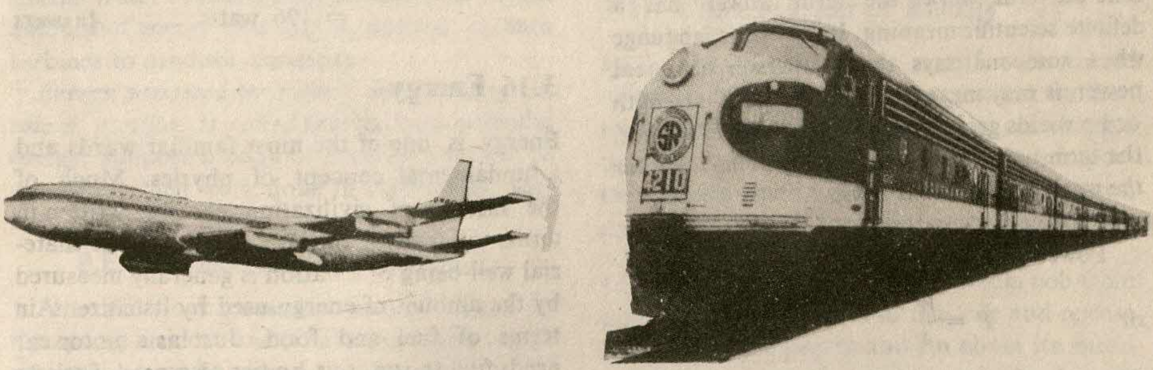


Fig. 3.9

3.14 Work

Some jobs like lifting of a box or moving it on the floor need fuel, others like supporting a car on a jack or floating of a boat on water need no fuel. In all those jobs which require some fuel or which involve the transfer of energy, work is said to be done. To be more specific we say that when a force acting on an object moves the latter through some distance work is done. It does not matter whether the force is accelerating the object such as taking off of a rocket or is simply moving it along, such as pushing of a car that has run out of petrol.

The amount of work done in lifting a box is greater when (1) the box is heavier; (2) it is raised higher. *The work done is defined to be equal to the force applied and the distance covered in the direction of the force.*

Work = force × displacement in the direction of force

$$W = F \times S$$

You know that force and displacement are vector quantities. However, work and energy do not have any particular direction, and so are scalar quantities.

The unit of force is newton and that of displacement is metre, thus the unit of work is Nm which is called the Joule, written as J. *One joule is the amount of work done when a force of 1N acts through a distance of 1m.*

1 Joule = 1 newton × 1 metre

or $1\,J = 1N \times 1m = 1Nm$

However hard we may push a wall, scientifically no work is done, as $S = 0$, therefore,

$W = F \times S = 0$. Similarly on holding a load in hand no work is done. Actually there is some contraction of muscles and some internal work is done. That is why we get tired on holding a brick for some time. On the other hand, once a space craft is out of the influence of gravity, it keeps going with uniform speed and would need no force, and hence no work, to do so.

EXAMPLE 2. A box of mass 2 kg is pushed along a floor through 2 m against a force of friction of 5N. The same mass is lifted up through a height of 2 m. If $g = 9.8\ \text{m/s}^2$, calculate the work done in both the cases.

Given Force of friction = 5 N
Force of gravity = $2 \times 9.8 = 19.6$ N
Distance moved in direction of force = 2 m

To find Work done = ?

Solution

Work done against friction = $5\ \text{N} \times 2\ \text{m}$
= 10 J *Answer*

Work done on lifting = $19.6\ \text{N} \times 2\ \text{m}$
= 39.2 J *Answer*

3.15 Power

Like the term *'work'*, the term *'power'* has a definite scientific meaning. In layman's language when someone says that a person has great power, it may mean that he has great strength or he wields great political authority; in science, the term **power** *means the rate of doing work, or the work done per unit time.*

$$\text{Power (W)} = \frac{\text{work done (J)}}{\text{time taken (s)}}$$

or

$$P = \frac{W}{t}$$

The unit of power is **watt**. If in one second, work done is 1 Joule, then the power is 1 watt.

It is obvious that power not only depends upon the amount of work done but also on the time taken in doing the work. For example, a worker carries 200 bricks to the top of a loading ramp in 1 hour while a crane does the same job in half a minute. While the amount of work done is the same in both cases, the power of the crane is 120 times that of the worker.

For practical purposes, watt, the unit of power, is rather small; a larger unit called the *kilowatt* is used.

1 kilowatt (kW) = 1000 watt (W)

In industry, power is measured by a unit called the *horse power* (hp) which is equal to approximately 750 watts. The power of a steam engine is 1000 to 4000 horse power and that of a truck is 60 to 300 horse power.

EXAMPLE 3. A boy of mass 50 kg climbs up a flight of stairs of height 12 m in 30 seconds. Calculate his power, when $g = 9.8\ \text{m/s}^2$.

Given Force of gravity = $50 \times 9.8 = 490$ N
Distance moved = 12 m
Time taken = 30 s

To find Power = ?

Solution

As Work = force × distance

$\therefore$ $W = 490\ \text{N} \times 12\ \text{m} = 5880\ \text{J}$

As $\text{Power} = \dfrac{\text{work done}}{\text{time}}$

$\therefore$ $\text{Power} = \dfrac{5880}{30}$

= 196 watts *Answers*

3.16 Energy

Energy is one of the most familiar words and a fundamental concept of physics. Much of the history of civilization can be written in terms of control and use of energy. The material well-being of a nation is generally measured by the amount of energy used by its citizens in terms of fuel and food. Just as a motor car needs fuel to run, our bodies also need fuel to perform various activities. This fuel is supplied in the form of food. Food enables us not only to breathe and think, but also to do jobs like running, lifting loads or playing games.

Work is the evidence to recognize the presence of energy and an object acquires energy when work is done on it. **Energy** *is the ability to do work and is equal to the work done on the body.* It is measured in Joules, which is the unit of work also. Like work, energy is a scalar quantity.

Since the Joule is a small unit of energy, the unit of energy which is used in industry is 1 kWh (kilowatt hour)

$$1\ \text{kWh} = 1\ \text{kW} \times 1\ \text{hour}$$
$$= 1000\ \text{W} \times 3600\ \text{s} = 3{,}600{,}000\ \text{J}$$

Kinetic Energy

Running water of a turbulent stream can wash away a bridge and can also be put to use to turn a turbine to produce electrical energy. Similarly a blowing wind can uproot trees and can also move the vanes of a wind-mill.

Moving matter possesses energy due to motion called kinetic energy. **Kinetic energy** *is the energy possessed by an object by virtue of its motion.* It is given by the following expression.

$$\text{Kinetic energy} = \tfrac{1}{2}\ \text{mass} \times \text{velocity}^2$$

or $$\text{K.E.(J)} = \tfrac{1}{2}\, m\,(\text{kg}) \times v^2\ (\text{m/s})$$

Potential Energy

Any matter at a higher level has energy due to its raised position as it has the ability to do work while coming down due to the pull of the Earth. Water behind a dam possesses enormous amount of energy that can be utilized to turn turbines to produce electricity.

Energy passessed by a body by virtue of its raised position is called **gravitational potential energy**. Suppose a body of mass m is raised to a height h; then work done in raising the mass is equal to mgh. Hence

$$\text{P.E.(J)} = m(\text{kg}) \times g(\text{m/s}^2) \times h(\text{m})$$

A wound clock possesses energy stored in the spring inside it and is said to possess *elastic potential energy* by virtue of its condition.

3.17 Energy Transformations

Can you think of any other form of energy? On switching on a torch, the *chemical energy* stored in the cell appears as *heat* and *light* which are other forms of energy. Atomic and hydrogen bombs when exploded release huge amounts of energy due to the conversion of *nuclear energy* to heat, light, *sound* and *pressure* energy.

Activity 7. Hammer a piece of lead or any other metal a few times. Touch the metal and you will find that it has become warm. What are the energy changes? You could write the energy changes as follows:

Chemical Energy → *Potential Energy* →
(of food in your body) (in hammer when it is raised up)
Kinetic Energy → *Heat Energy*
(in hammer during fall) (in metal and hammer)

In steam engines, coal is burnt to produce heat which changes water into steam at high pressure; this in turn moves the piston and wheels. Energy changes can be written as follows:

Chemical Energy → *Heat Energy* →
(coal used as fuel) (produced during burning)
Internal Energy → *Kinetic Energy*
(possessed by high pressure steam) (moving piston and wheels)

3.18 Conservation of Energy

In the examples of energy transfer mentioned above, energy of one form changes into another, and sometimes there are more than one changes before it appears in the final form. It is important to note that in each of the above cases, energy was transferred *from one kind to another.*

Activity 8. Support a heavy pendulum bob from a rigid stand; displace it to one side and release it. It starts swinging to and fro about its mean position.

The bob momentarily comes to rest at the extreme end of each swing and the energy it possesses in this position is gravitational potential energy. As it swings towards the mean position the potential energy changes to kinetic

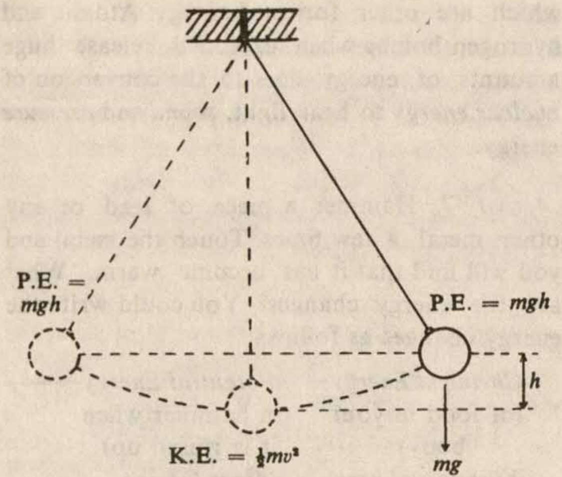


Fig. 3.10

energy. At the mean position the kinetic energy = $\frac{1}{2}mv^2$ has been gained from the loss in potential energy of *mgh*. The bob again rises to the other side. Thus there is an interchange of kinetic and potential energy. Would this go on indefinitely?

In actual practice, some of the energy is wasted as heat, due to friction at the suspension and air resistance. If the suspension were made frictionless and the pendulum made to vibrate in vacuum, the interchange K.E.$\rightleftharpoons$P.E. would go on forever. This leads to the **Principle of Conservation of Energy** *which states that energy can neither be created nor destroyed but changes its form from one to another; the sum total of all energy remains constant.*

It is important to note that at each transfer of energy, some energy is changed in the form of heat which cannot be recovered easily for doing useful work. Although heat can be changed into other kinds of useful work, such as in the heat engines, less and less of energy becomes available for useful jobs as every energy transformation releases waste energy. The ultimate fate of every kind of energy is heat energy at low temperature from which it is difficult to obtain useful work.

QUESTIONS

1. Define force. Name and define the unit of force.

2. State the First Law of Motion and give two examples to explain it. Does the law apply in the case of (a) a car moving on a straight road at a uniform speed of 60 km/hour; (b) a lift moving upward at a constant speed of 2 m/s?

3. A player kicks a ½ kg football and gives it a speed of 14 m/s starting from rest. If the contact between the foot and the football was of 0.02 second, calculate the force applied by the foot.

4. An object of mass 5 kg is accelerated by 4 m/s² from east to west. How large is the force and in which direction does it act?

5. A certain force exerted for 1.4s raises the speed of an object from 1.8 m/s to 4.6 m/s. If this force is continued further for a period of 2.0 s, how much will the speed become?

6. An object initially at rest is given a push. How does the acceleration of the object depend upon the force applied? If the force is doubled, how does (a) the acceleration, (b) the distance travelled in one second, change?

7. A space ship attains a velocity of 5×10^4 km/hour in space. How could it continue to go at this speed? How could it turn back to the Earth?

8. On which principle is the working of a rocket based? Explain.

9. Distinguish between mass and weight. How do these quantities vary for an object on the Earth and on the Moon's surface?

10. If the mass of an object is doubled but the force acting on it remains unchanged, how would the acceleration alter? Discuss the meanings of the terms used.

11. A force of 8 N gives a mass m_1 an acceleration of 2 m/s² and a mass m_2 an acceleration

of 4 m/s^2. Find the value of each mass and find the acceleration produced in the combination of the two when the same force acts on it.

12. When a force of 10^{-20} N acts on an electron, it produces in it an acceleration of 10^{10} m/s^2. Find the mass of the electron.

13. When does a force do work? How is the work done measured?

14. A cable car is pulled up by a force of 500 kgf. Travelling at 5m/s, it takes 200 s to reach the top of a hill. Calculate the amount of work done.

15. A man raises a mass of 15 kg through 2 m and holds it there for 10 seconds. What is the amount of work he has done?

16. What happens to the energy when work is done against (a) friction, (b) gravity and (c) inertia?

17. What is meant by the term power? Which of the following are the units of power: Kilowatt, Newton, Horse Power, Joule, Newton-metre.

18. What is the difference between work and energy? How are they measured and in which units are they expressed?

19. Define kinetic and potential energy. What is the principle of conservation of energy?

20. A car of mass 500 kg accelerates from rest to 20 m/s in a distance of 100 m.

(a) What is the acceleration?
(b) What is the work done by the engine?
(c) What is the final kinetic energy?
(d) What is power developed by the engine?

21. Which of the following statements (if any) are correct? When the velocity of a moving object is doubled in one second:
(a) its kinetic energy is doubled; (b) its momentum is doubled; (c) its acceleration is doubled; (d) its potential energy is doubled; (e) its power is doubled.

22. 300 kg of air moving at 10 m/s impinges on the vanes of a windmill every minute. At what rate is the energy being given to the windmill.

23. Two teams pull a rope in a tug-of-war, but the result is a draw even after a few minutes. Mention the energy transformations taking place.

24. State the energy changes which take place in the following examples:

(a) a speeding car is brought to rest by applying brakes;
(b) the swinging of a pendulum;
(c) a bicycle dynamo lights a lamp;
(d) an electric ball is worked with a torch cell;
(e) a Diwali rocket is fired from the ground;
(f) scooter lights are switched on;
(g) a toy car is wound and allowed to run upwards on an inclined table.

25. Explain the meaning of the term 'sliding friction'. Give three practical examples in which friction is troublesome, and three in which it is useful. Mention three ways of reducing friction in machines.

26. State the laws of friction and define coefficient of friction.

27. A block of mass 2.5 kg rests on a surface. The force of friction between the two surfaces is 5N. If a force of 25N acts on the block, find the acceleration with which the block will move.

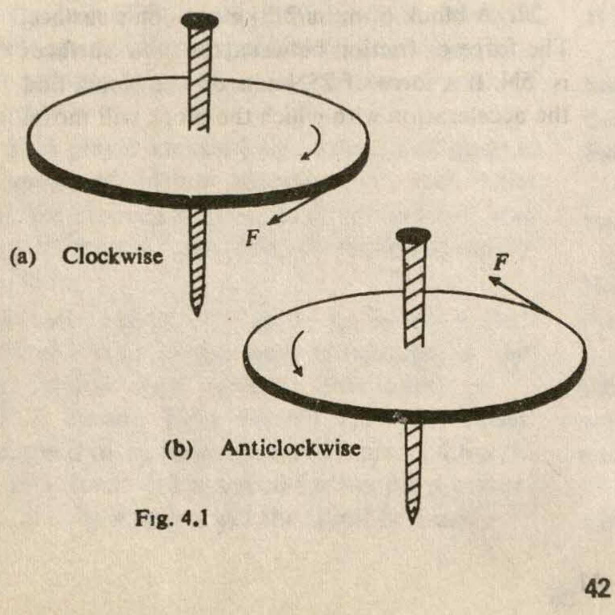
4

Moment of Force and Simple Machines

Force not only changes velocity, size and shape of an object but can also rotate it about an axis. A smaller boy can balance a heavier one on a see-saw by sitting away from the axis, and a pipe is slipped on a wrench to increase the length of its handle to open a rusted nut. Knobs and handles are provided near the edge of a door away from the hinges. These and many other facts can be explained by the moment or turning effect of a force, which finds many applications in simple machines.

4.1 Moment of a Force or Torque

Activity 1. Take a cardboard disc and fix it loosely with a nail on a table. Apply a force on it *tangentially* (Fig. 4.1). You will find that the disc rotates about the nail either clockwise or anticlockwise depending upon the direction of the force applied.



(a) Clockwise

(b) Anticlockwise

Fig. 4.1

The tendency of a force to turn an object about an axis or a point is called the moment of force about that axis or point. It is a vector quantity as the moment can be either anticlockwise or clockwise. Anticlockwise moment is usually taken as positive. Let us find out on what factors the magnitude of the moment of force depends.

Activity 2. Take a half metre scale with an arrangement as shown in Fig. 4.2 to balance the scale in the middle. In case the scale does not balance exactly stick some plasticine to one side to exactly balance it. Now place a 10 paise coin at some distance to the left of the fulcrum and observe the amount of turning produced.

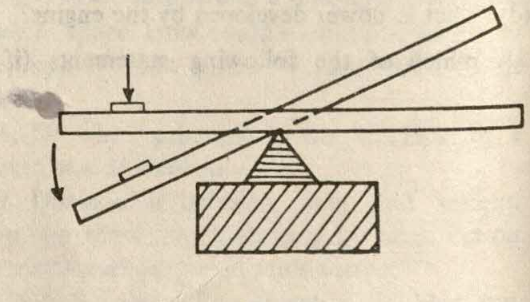


Fig. 4.2

It is found that the turning effect of force becomes more if the coin is moved away from the fulcrum and when one 10 paise coin is replaced by two 10 paise coins. The combined effect of the force and the distance determines the magnitude of turning effect, called the moment of force.

The **moment of force** about a point or an axis *is the turning effect of a force and is equal to the product of the force and the perpendicular distance between the line of action of force and the point or axis of rotation.*

Moment of force = force × perpendicular distance of the point from the line of action of force.

Or

Moment of force (Nm) = force (N) × moment arm (m)

Suppose a force F acts on a body capable of rotation about O. From O drop a perpendicular OP on the line of action of force as shown in Fig. 4.3.

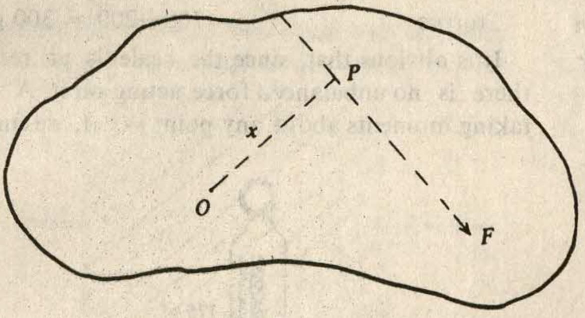


Fig. 4.3

Then, moment of force $M = F \times OP$

$= F \times x$ Nm

EXAMPLE 1. A force of 4N acts at a distance of 40 cm from the axis of rotation; calculate its moment. How far away from the axis should a force of 5 N act to produce the same moment?

Given $F_1 = 4$ N

$d_1 = 0.40$ m

$F_2 = 5$ N

To find $M_1 = ?$

$d_2 = ?$

Solution

$$M_1 = F_1 d_1 = 4\ \text{N} \times 0.4\ \text{m} = 1.60\ \text{Nm}$$ *Answer*

$M_2 = 5\ \text{N} \times d_2$

As $M_2 = M_1$

$\therefore$ $5d_2 = 1.6$

and $d_2 = 0.32$ m or 32 cm *Answer*

4.2 Principle of Moments

Activity 3. Take a metre scale and balance it on a knife edge. A uniform metre scale should balance at 50.0 cm mark; if there is a slight difference, stick some plasticine to one side to balance it at 50.0 cm mark. Throughout the experiment, keep the knife edge at the same position.

Suspend two loads of 100 gf by cotton threads from either side of the knife edge and adjust their positions in such a way that the scale is balanced horizontally (Fig. 4.4a). There could be many positions of the loads when the scale can be balanced. Calculate clockwise and anticlockwise moments. What do you find?

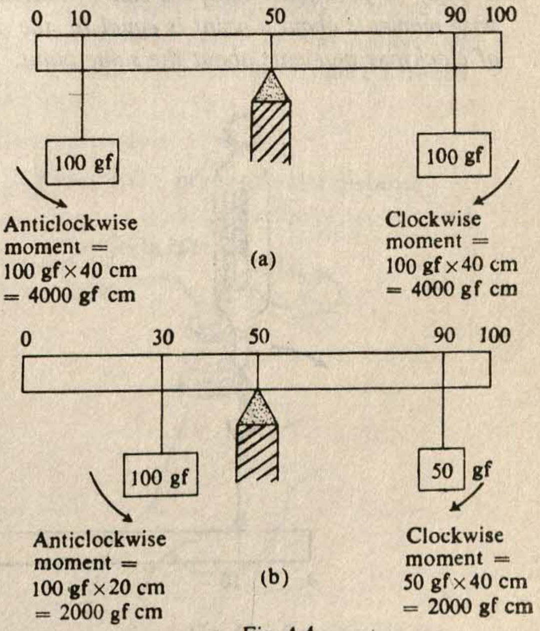

0
10
50
90
100
100 gf
100 gf
Anticlockwise moment = 100 gf × 40 cm = 4000 gf cm
(a)
Clockwise moment = 100 gf × 40 cm = 4000 gf cm
0
30
50
90
100
100 gf
50 gf
Anticlockwise moment = 100 gf × 20 cm = 2000 gf cm
(b)
Clockwise moment = 50 gf × 40 cm = 2000 gf cm

Fig. 4.4

Now suspend a 100 gf load from one side, say from the 30.0 cm mark and from the other side suspend a 50 gf load and adjust its position so that the scale is again balanced. Calculate both the moments as shown in Fig. 4.4b. It is also possible to balance the scale using more than two loads as shown in (Fig. 4.5).

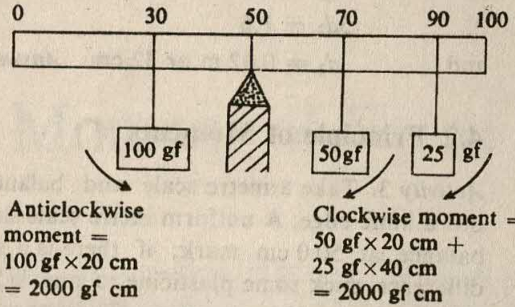

0
30
50
70
90
100
100 gf
50gf
25 gf
Anticlockwise moment = 100 gf×20 cm = 2000 gf cm
Clockwise moment = 50 gf×20 cm + 25 gf×40 cm = 2000 gf cm

Fig. 4.5

In all the above cases, it is observed that the sum of anticlockwise moments is equal to the sum of clockwise moments. This is the principle of moments.

According to the **principle of moments,** *when a body is in equilibrium, the sum of anticlockwise moments about a point is equal to the sum of clockwise moments about the same point.*

4.3 Parallel Forces

Parallel forces which act in the same direction are called **like parallel forces;** those which act in opposite directions are called **unlike parallel forces.**

Activity 4. Suppose a metre scale of weight 100 gf is suspended by two vertical threads attached to two spring balances held by clamp stands. A load of 200 gf is suspended from the scale from the 60 cm mark as shown in Fig. 4.6. The weight of the uniform metre scale acts at the 50.0 cm mark vertically downward; this is the point from where the scale can be balanced when suspended freely over a knife edge. The spring balances are raised or lowered to make the scale hang horizontally. Note the readings as shown by the spring balances. These are recorded on the diagram.

The sum of upward forces

$$= 125+175 = 300 \text{ gf}$$

The sum of downward forces

$$= 100+200 = 300 \text{ gf}$$

It is obvious that, since the scale is at rest, there is no unbalanced force acting on it. Also taking moments about any point say A, we find

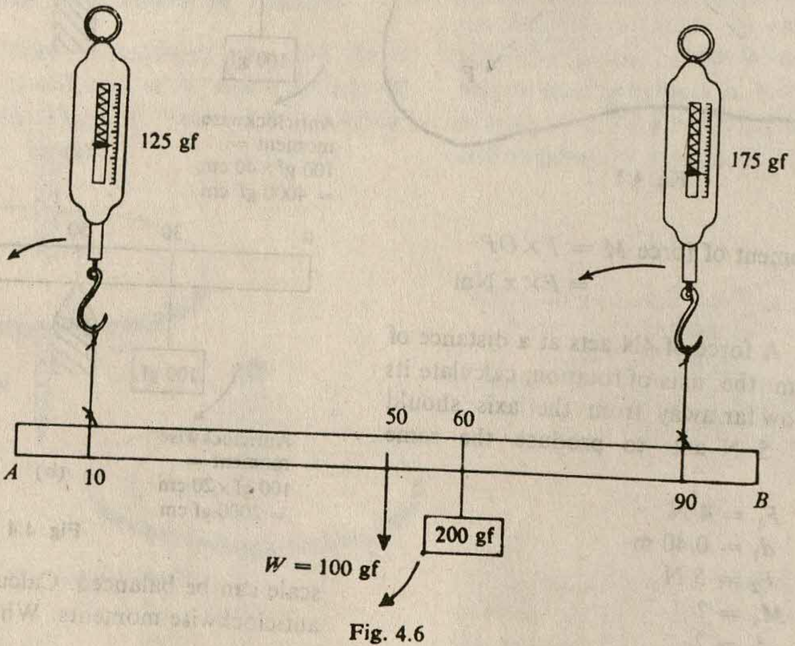


Fig. 4.6

that the sum of anticlockwise moments is equal to the sum of clockwise moments

Sum of clockwise moments

$$= 100\text{ gf} \times 50\text{ cm} + 200\text{ gf} \times 60\text{ cm}$$
$$= 17{,}000\text{ gf cm}$$

Sum of anticlockwise moments

$$= 125\text{ gf} \times 10\text{ cm} + 175\text{ gf} \times 90\text{ cm}$$
$$= 17{,}000\text{ gf cm}$$

We arrive at the general rule that when a number of parallel forces acting on an object keep it in equilibrium, (i) the sum of forces in one direction is equal to the sum of forces in the opposite direction (or the vector sum of forces is zero); and (ii) the sum of anticlockwise moments about any point is equal to the sum of clockwise moments (or the 'algebraic' sum of moments of all forces about any point is zero).

4.4 Moment of a Couple

Consider the action of two equal and opposite forces acting on a block as shown in Fig. 4.7.

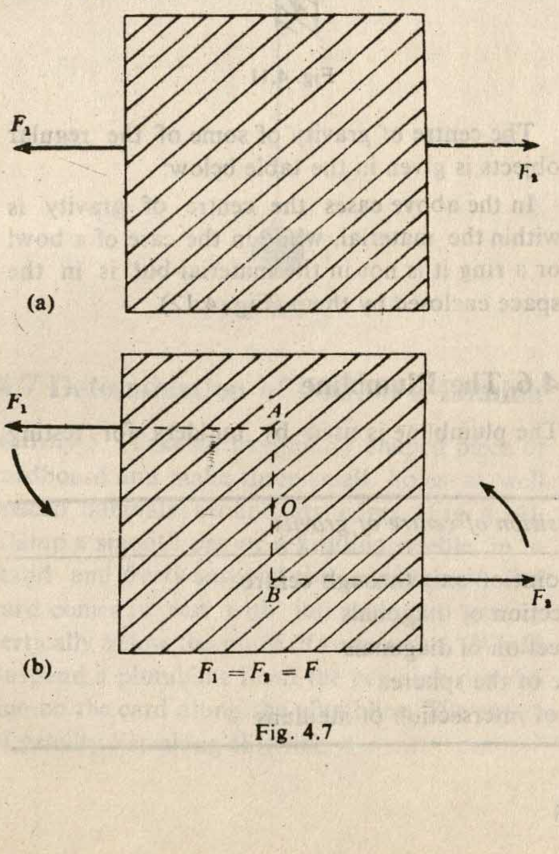


Fig. 4.7

These two forces act along the same straight line and are therefore balanced; if the block is originally at rest, it will continue to be in the same state of rest.

In Fig. 4.7b, two equal and opposite forces are shown, but these are not acting in the same straight line. The vector sum of the two forces will be zero; the block therefore, will not have any *translatory motion*. However, if moments are taken about a point O, these will add to produce a turning effect and the block will rotate in the anticlockwise direction.

Anticlockwise moment of F_1 about O

$$= F_1 \times OA = F \times OA$$

Anticlockwise moment of F_2 about O

$$= F_2 \times OB = F \times OB$$

The resultant moment due to F_1 and F_2

$$= F(OA + OB) = F \times AB$$

= Force × perpendicular distance between the two forces

A pair of two equal, opposite and parallel forces form a **couple** *which tends to rotate the object. Its moment is equal to the product of the force and the perpendicular distance between the two forces.*

Moment of couple (Nm)

= Force (N) × perpendicular distance between the two forces (m)

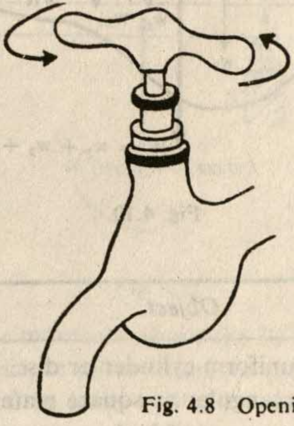


Fig. 4.8 Opening of a tap

While opening a tap, two opposite parallel forces are applied by the thumb and the forefinger. The other examples of moment of couple are the unscrewing of the screw cap of a bottle and threading of a nut into a bolt as shown in Fig. 4.9a and b.

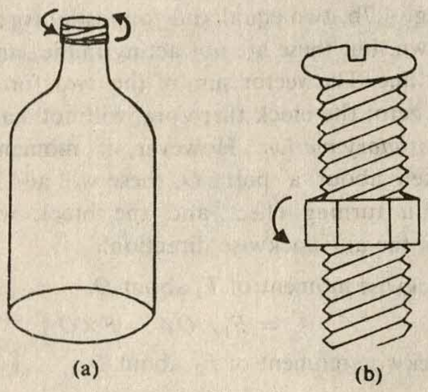


Fig. 4.9

4.5 Centre of Gravity

An object may be considered to be made up of a very large number of small particles each of which is being pulled down towards the Earth by a force equal to its weight. Thus, a number of small parallel forces act on the object, the sum of which is the total weight of it. As shown in Fig. 4.10, the resultant of all the like parallel forces is equal to the weight of the object acting through a single point called the centre of gravity.

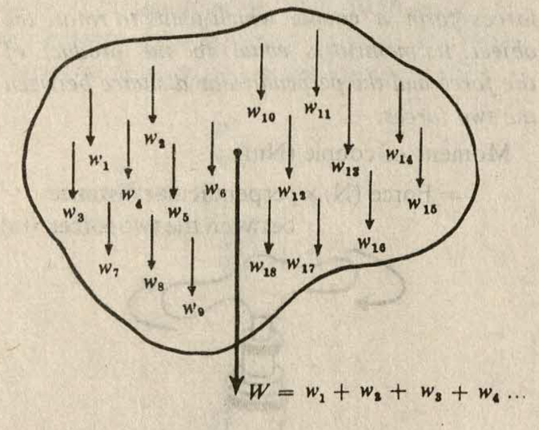


Fig. 4.10

The **centre of gravity** (C.G.) *is a point where the weight of a body acts.* It is also the point where a body can be balanced. For example, the C.G. of a scale is a point where it can be balanced on a sharp edge. In a uniform metre scale it is at 50.0 cm mark. At this point the weight of the scale acts vertically downward and an equal and opposite reaction R of the support acts upwards, see Fig. 4.11. These two forces lie in the same straight line so that they cancel each other and the vector sum of their moments about any point is zero.

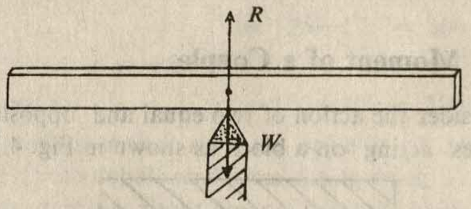


Fig. 4.11

The centre of gravity of some of the regular objects is given in the table below:

In the above cases the centre of gravity is within the material, while in the case of a bowl or a ring it is not in the material but is in the space enclosed by them (Fig. 4.12).

4.6 The Plumbline

The plumbline is used by builders for testing

Object	*Position of centre of gravity*
1. A uniform cylinder or disc	Mid point of axis through centre
2. Rectangular or square plate	Intersection of diagonals
3. Rectangular block	Intersection of diagonals
4. A spherical bob	Centre of the sphere
5. A triangular sheet	Point of intersection of medians

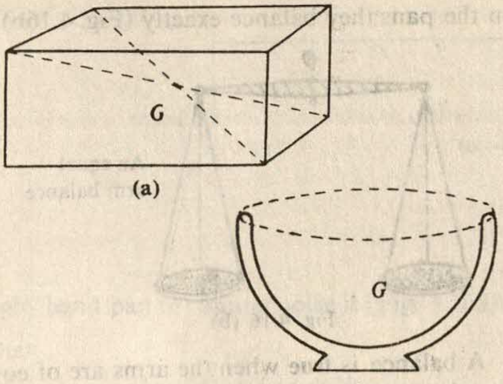


Fig. 4.12

the uprightness of walls. It consists of a small heavy bob supported by a thin cord. The force of gravity, equal to the weight of the system, acts vertically downwards. It is balanced by the tension in the cord. The cord sets itself vertically so that the two forces are in one line (see Fig. 4.13).

Fig. 4.13

4.7 Determination of C.G. of a Lamina

Activity 5. Take an irregularly shaped piece of cardboard and make three small holes at well spaced intervals around its edges (Fig. 4.14). Clamp a smooth peg or a knitting needle in a stand and *freely* suspend the card from it. The card comes to rest with its centre of gravity vertically below the point of suspension. (Why?) Suspend a plumbline from the peg and draw a line on the card along the plumbline. The centre of gravity lies along this line.

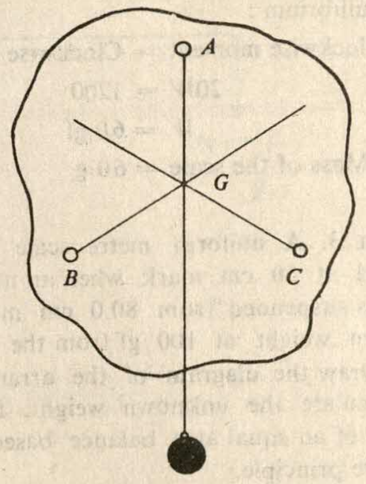


Fig. 4.14

Now repeat the experiment by suspending the card first from hole B and then from the hole C. The centre of gravity is the intersection of the three lines drawn through the points of suspension.

EXAMPLE 2. A uniform metre scale can be balanced at 70.0 cm mark when a load of 50 gf is hung from 94.0 cm mark. Draw a diagram of the arrangement, showing various forces acting on the scale and find out its mass.

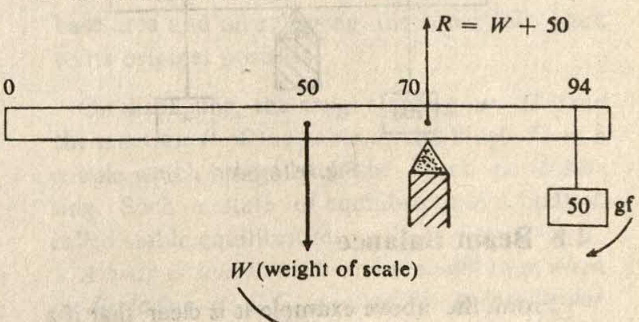


Fig. 4.15

Consider moments about the 70.0 cm mark.
Anticlockwise moment due to the
weight of the scale $= W(70 - 50)$
$= 20W$ gfcm

Clockwise moment $= 50(94 - 70)$
of 50 gf $= 50 \times 24$
$= 1200$ gfcm

In equilibrium :

Anticlockwise moment = Clockwise moment

$$20W = 1200$$

$$\therefore \quad W = 60 \text{ gf}$$

Mass of the scale = 60 g *Answer*

EXAMPLE 3. A uniform metre scale can be balanced at 50 cm mark when an unknown weight is suspended from 80.0 cm mark and a known weight of 100 gf from the 20.0 cm mark. Draw the diagram of the arrangement and calculate the unknown weight. Draw a diagram of an equal arm balance based upon the above principle.

Consider moments around the 50.0 cm mark:

Clockwise moment $= x(80 - 50) = 30x$ gfcm

Anticlockwise moment $= 100(50 - 20)$

$= 3000$ gfcm

In equilibrium:

$$30x = 3000$$

$$\therefore \quad x = 100 \text{ gf}$$

Mass of the object = 100 g *Answer*

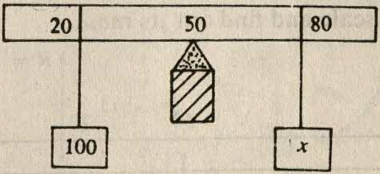


Fig. 4.16 (a)

4.8 Beam Balance

From the above example it is clear that if a beam pivoted at its centre of gravity and having two weights suspended at equal distances on either side from the point of suspension, remains balanced, then the weights are of equal masses. This is the principle of the **beam balance**.

An equal arm balance consists of a beam supporting pans of equal masses at either end. It has an arrangement for suspending the beam from the centre. When no extra weights are put on the pans they balance exactly (Fig. 4.16b).

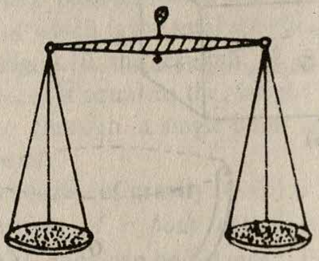

An equal arm balance

Fig. 4.16 (b)

A balance is **true** when the arms are of equal length and the pans are of the same mass. A true balance stays balanced when either equal weights are put or no extra weights are put in the two pans. A balance is faulty when either the pans are of unequal masses, the arms are of unequal lengths, or when both these faults are present. The technique of **double weighing** is used to weigh correctly with a faulty balance.

(i) *Pans are of Unequal Weights*

Activity 6. Put the object to be weighed in the left hand pan and put weights in the right hand pan to balance it. Let the value of the weight be w_1. Now put the object in the right hand pan and weights in the left hand pan to balance it. Let the value of the weights be w_2. Then

$$\text{True mass of object} = \frac{w_1 + w_2}{2}$$

(ii) *When Arms are of Unequal Lengths*

Let the lengths of the arms be a and b, and the masses of the two pans be p and q respectively. The balance remains horizontal when the pans are empty. Hence, according to the principle of moments,

$$pa = qb \qquad \text{(i)}$$

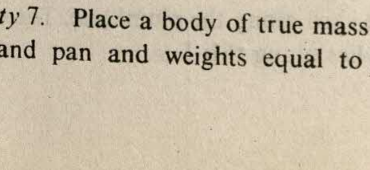


Fig. 4.16(c)

Activity 7. Place a body of true mass w in the left hand pan and weights equal to w_1 in the

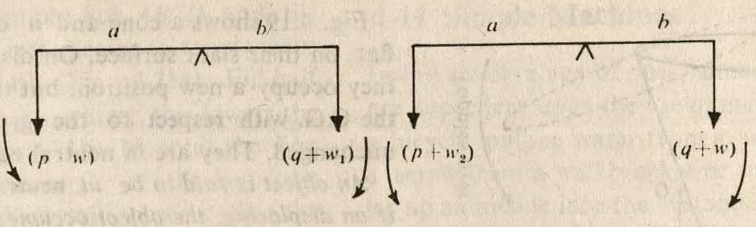


Fig. 4.16(d)

right hand pan to counter poise it (Fig. 4.16d).

Then

$$(p+w)a=(q+w_1)b$$

or

$$pa+wa=qb+w_1b$$

Now since $pa=qb$, we have

$$wa=w_1b \qquad \text{(ii)}$$

Now place the object in the right hand pan and weights equal to w_2 in the left hand pan to counterpoise it.

Then

$$(q+w)b=(p+w_2)a$$

$$qb+wb=pa+w_2a$$

or

$$wb=w_2a \qquad \text{(iii)}$$

From equations (ii) and (iii) we have

$$wa\times wb=w_1b\times w_2a$$

or

$$w^2=w_1w_2$$

or

$$w=\sqrt{w_1w_2}$$

The true mass of the body can thus be calculated.

4.9 States of Equilibrium

From common experience you know that on lifting a book lying on a table it easily comes back to its original position, a pencil balanced on its flat end topples over and a cylinder lying lengthwise rolls over when displaced.

Activity 8. Place a rectangular block on a horizontal table and raise one of its ends through about an angle of approximately 45° (see Fig. 4.17). The C.G. of the block is raised from G to G'; the perpendicular from the new position of centre of gravity G' falls within the base area and on releasing, the block falls back to its original position.

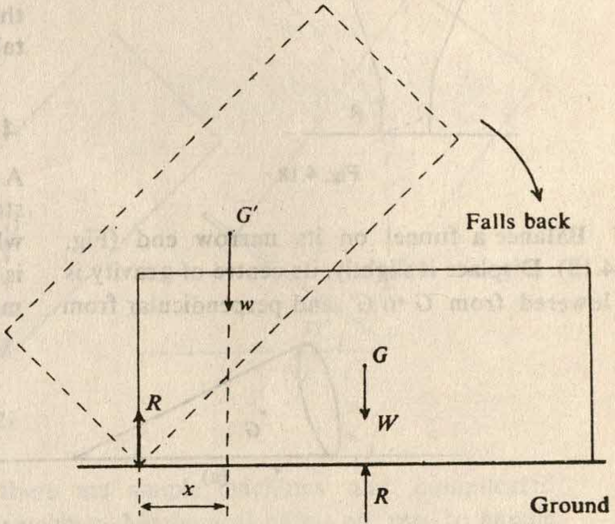


Fig. 4.17

On displacing, the weight acting on G' and the reaction R of the table on the block, form a couple which brings back the block on releasing. Such a state of equilibrium of a body is called stable equilibrium.

A body is said to be in **stable equilibrium** *when on displacing, its C.G. is raised; the perpendicular from the C.G. falls within the base area and it comes back to its original position* e.g. a Bunsen burner standing on its base.

When a man carries a heavy load on his back, his C.G. is displaced towards the load. The perpendicular from the C.G. might then fall outside the base area formed by the man's legs and he might topple over. To avoid this he bends forward so that the perpendicular now falls within the base area.

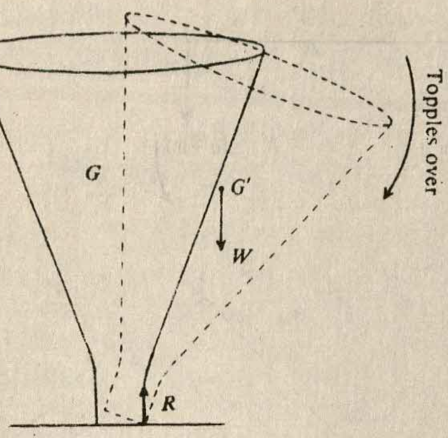
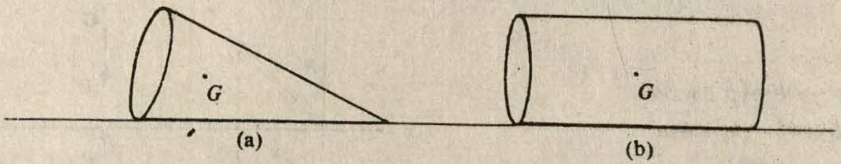


Fig. 4.18

Balance a funnel on its narrow end (Fig. 4.18). Displace it slightly; its centre of gravity is lowered from G to G' and perpendicular from G' falls outside the base area. The reaction R and the weight W acting on G' form a couple which topples over the funnel. The funnel is in unstable equilibrium.

An object is said to be in **unstable equilibrium** *if on displacing, the C.G. is lowered; the perpendicular from the C.G. falls outside the base area and the object topples over.*



(a) (b)

Fig. 4.19

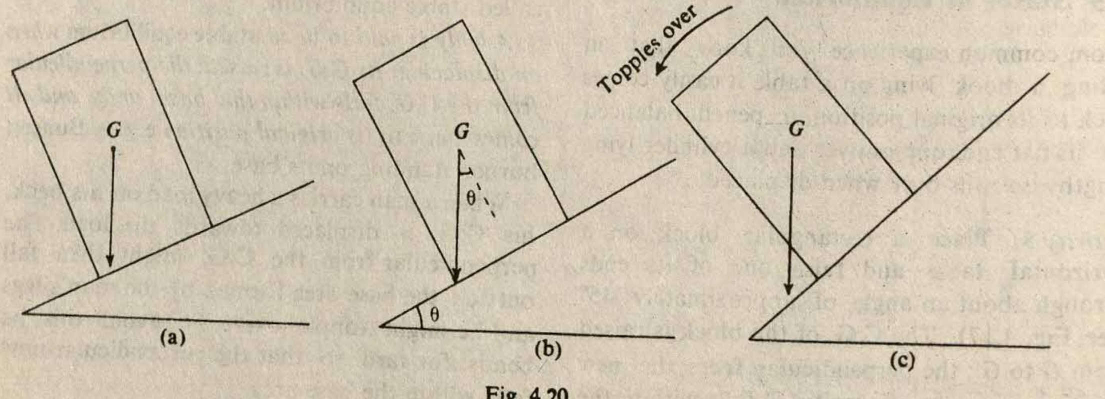
Fig. 4.19 shows a cone and a cylinder lying flat on their slant surface. On displacing them, they occupy a new position, but the position of the C.G. with respect to the ground remains unchanged. They are in neutral equilibrium.

An object is said to be in **neutral equilibrium** *if on displacing, the object occupies a new position and the position of C.G. remains unchanged.* The vertical line through the C.G. always passes through the base which is in contact with the table top.

4.10 Stability

A man standing with his legs wide apart is more stable than one standing on one leg. A body which offers greater resistance to toppling over, is said to possess greater *stability*. Stability is measured by the angle θ through which a body can be tilted before being toppled over (see Fig. 4.20).

When the body is displaced through an angle less than $\angle\theta$ as shown in Fig. 4.20a, it recovers its original position on releasing. On displacing it through an angle greater than $\angle\theta$, the body topples over on releasing (Fig. 4.20c).



(a) (b) (c)

Fig. 4.20

Activity 9. Take an empty box *ABCD* and tilt it gradually till it just begins to topple over; measure the angle of tilt (Fig. 4.21a). Fill half the box with sand or water; this lowers the centre of gravity (Fig. 4.21b). Now tilt the box again and find out the angle of tilt before it becomes unstable. You will observe that the angle of tilt is much greater now. Thus, stability depends upon the position of the centre of gravity; *by lowering the centre of gravity the stability increases*.

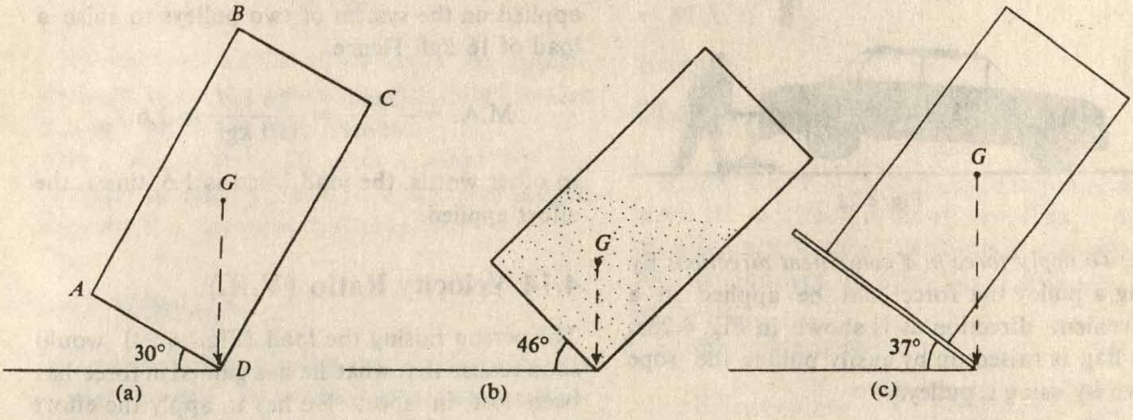


Fig. 4.21

Now remove the sand and attach a stiff card sheet of negligible weight to the base so that the base area is increased (Fig. 4.21c). Tilt the box again till it just begins to topple over; measure the angle of tilt. You will observe that the angle of tilt is more. Thus, greater the base area, more is the stability; *by increasing the area of the base the stability increases.*

The centre of gravity of a double-decker bus is higher than that of an ordinary bus. This is why it is more likely to topple over. The lower deck of the double-decker bus is, therefore, first occupied by passengers to keep the C.G. low and to increase its stability. A tight-rope walker usually carries a long pole which sags at the ends and lowers the centre of gravity to increase stability. A person standing on one foot is less stable than one standing on both the feet; a person sitting on a chair is more stable than one who is standing.

4.11 Simple Machines

In this modern age of ours, almost all activities are dependent upon the use of machines. Riding a bicycle, pulling water from a well, removing a screw from a wall bracket or pushing a scooter up an incline into the verandah, are examples where a simple machine is in use. However, there are simple machines and complicated machines. Mechanical hands are used to handle radioactive materials from a distance and automobile engines are assembled in an intricate way using a number of parts. If you observe a mechanical hand, a car engine or any other complicated machine, you will find that they are really a combination of many simple machines: pulley, lever, gear, screw, inclined plane, etc.

4.12 What is a Machine?

Machine is a device on which when work is done by applying effort through a certain distance at one point, it does work in overcoming resistance through some distance at another point. The work done on a machine is called *input energy* and work done by the machine is called *output energy*. The output energy is always less than the input energy because some of the energy is wasted in overcoming friction, etc. The question that naturally arises, therefore, is why we use machines at all. Machines help us in three ways:

1. *To multiply force:* A greater load or resistance can be overcome by applying a much smaller effort; for example with a jack screw a man can lift one side of a car to replace a flat tyre (Fig. 4.22).

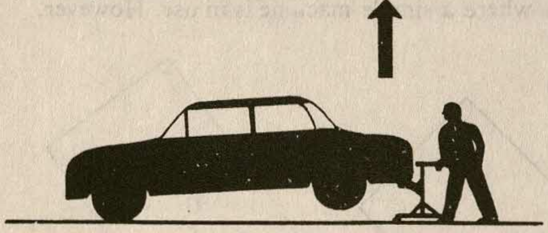


Fig. 4.22

2. *To apply force in a convenient direction:* By using a pulley the force can be applied in a convenient direction as is shown in Fig. 4.23a. The flag is raised up by easily pulling the rope down by using a pulley.

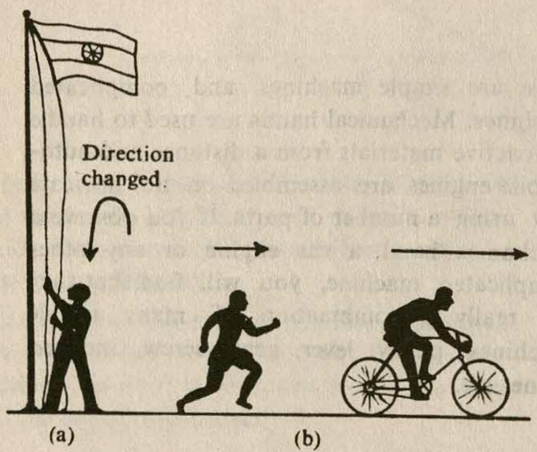


Fig. 4.23

3. *To gain speed*: A bicycle enables us to cover a great distance by pushing pedals through a small distance (Fig. 4.23b).

4.13 Mechanical Advantage (M.A.)

The force that we apply to a machine is called the *effort*; the force which a machine overcomes is called a *load*. Machines are usually designed to overcome a greater load by a small effort and the ratio of the load overcome to the effort applied is called its mechanical advantage (M.A.).

Mechanical advantage, M.A. (No unit)

$$= \frac{\text{Load, } L(\text{N or kgf})}{\text{Effort } E(\text{N or kgf})}$$

In Fig. 4.24 an effort of 10 kgf is being applied on the system of two pulleys to raise a load of 16 kgf. Hence

$$\text{M.A.} = \frac{\text{load}}{\text{effort}} = \frac{16 \text{ kgf}}{10 \text{ kgf}} = 1.6$$

In other words, the load lifted is 1.6 times the effort applied.

4.14 Velocity Ratio (V.R.)

The person raising the load (Fig. 4.24) would soon realise that what he has gained in force has been lost in speed. He has to apply the effort through a distance of 60 cm in order to raise the load through 30 cm, at the same time. *The ratio of the distance through which the effort is applied to the distance through which the load is overcome is called the velocity ratio.*

Velocity ratio, V.R.

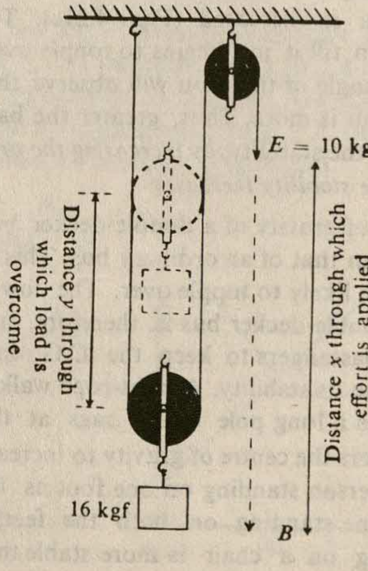

E = 10 kgf
Distance y through which load is overcome
Distance x through which effort is applied
16 kgf
B

Fig. 4.24

$$= \frac{\text{Distance through which effort is applied}}{\text{Distance through which load is overcome}}$$

Being a ratio, V.R. has no unit.

Velocity ratio depends upon the design of a machine. In the case of the system of pulleys, as shown in Fig. 4.24.

$$\text{V.R.} = \frac{60 \text{ cm}}{30 \text{ cm}} = 2$$

In other words, the effort has to be applied through twice the distance as compared to that through which the load is raised.

In a bicycle, the rider gains in speed but has to apply an effort greater than the force needed to move the bicycle with that speed.

4.15 Efficiency

In the above example, the load of 16 kgf was raised through 30 cm and hence gained potential energy. This energy came from the work done in applying an effort through a distance of 60 cm. In this example of energy transformation, taking g as 10 m/s^2, we have

Output energy = useful work done by the machine in moving the load
= 16 kgf × 30 cm
= 160N × 0.3 m = 48 J

Input energy = work done on the machine by the application of effort
= 10 kgf × 60 cm
= 100N × 0.6 m = 60 J

Thus, in all other examples of energy conversion too, the input energy is more than the output energy gained by the load; the difference is waste energy which mostly changes into heat energy. The waste energy is due to (a) the overcoming of friction between moving parts, and (b) raising the movable parts of the machine. Hence, we say that the efficiency of the machine is less than 100%.

Efficiency *of a machine is defined as the ratio of the output work done by the machine to the input work done on the machine.*

Efficiency =

$$\frac{\text{useful work done by machine in moving load}}{\text{work done on machine by application of effort}}$$

$$= \frac{\text{load} \times \text{distance moved by the load}}{\text{effort} \times \text{distance moved by the effort}}$$

$$= \frac{\text{load}}{\text{effort}} \times \frac{\text{distance moved by the load}}{\text{distance moved by the effort}}$$

$$= \text{M.A.} \times \frac{1}{\text{V.R.}}$$

Hence,

$$\text{Efficiency} = \frac{\text{M.A.}}{\text{V.R.}}$$

In practice, V.R. is always greater than M.A., hence the efficiency is always less than 1. When the efficiency obtained as above is multiplied by 100, the product is efficiency expressed as a percentage.

In the above example,

$$\text{Efficiency} = \frac{\text{output energy}}{\text{input energy}} = \frac{48 \text{ J}}{60 \text{ J}}$$

$$= 0.8 = 80\%$$

or $$\text{Efficiency} = \frac{\text{M.A.}}{\text{V.R.}} = \frac{1.6}{2}$$

$$= 0.8 = 80\%$$

As a rule, the efficiency of a machine varies with the load. If the load overcome is small, as compared to the weight of the movable part, in moving which some of the input energy is wasted, the useful work done will be a smaller fraction of the total input work, and the efficiency is low. If the load is large as compared to the weight of the movable part of the machine, the energy wasted is a small fraction of the input energy and the efficiency is high. In other words, assuming that the friction losses are almost constant, the efficiency of a machine increases with the increase of load upto a certain limit. Beyond this, the efficiency remains unchanged.

4.16 Single Fixed Pulley

A single fixed pulley consists of a grooved wheel which is mounted to a fixed framework called a *block*; the wheel is able to rotate about an axle without moving as a whole. A rope is passed over the pulley the load is attached to one of its ends and the effort E is applied at the other end (Fig. 4.25).

If the point of application of the effort moves down through a distance x, the load will move up by the same distance. Hence, V.R. = 1.

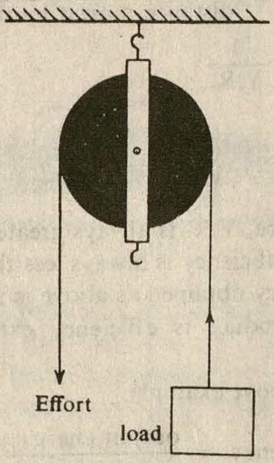


Fig. 4.25

If the pulley is frictionless and the weight of the rope is ignored the efficiency will be 1; hence,

$$\text{M.A.} = \text{Efficiency} \times \text{V.R.} = 1$$

or $$\text{Load} = \text{Effort}$$

Hence, ideally a single fixed pulley gains neither in force nor in speed; it merely changes the direction in which the force is applied. Such a pulley is usually employed in raising water from a well or small loads contained in a bucket to the top of buildings during construction. Raising a flag and fixing a tennis net are other examples.

4.17 Single Movable Pulley

The single movable pulley is suspended by a rope passing round it, with one end of the rope tied to a fixed support. The effort is applied to the other end.

If a load L is to be raised up through a vertical height y, the pulley itself will also move up along with the load; in order to achieve this, the effort will have to move through a distance $2y$ (Fig. 4.26). Thus V.R. = 2.

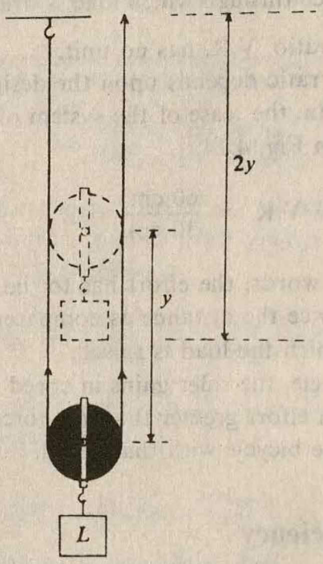


Fig. 4.26

In practice, besides overcoming friction, energy is wasted in lifting the pulley; hence, efficiency is never 100%. However, because of an increased V.R. as compared to a fixed pulley, the movable pulley is likely to have M.A. greater than unity. The direction of effort is inconvenient and usually one fixed pulley is added so that the effort is conveniently applied downwards (see Fig. 4.24).

4.18 Block and Tackle

The velocity ratio, and hence the mechanical advantage, of a pulley system can be increased by increasing the number of pulleys. Two such systems are shown in Figs. 4.27 and 4.28. Essentially they consist of two blocks, one of which is fixed to a rigid support and the other is movable. Each block may have equal number of pulleys, or the upper block may have one more. A single rope (*tackle*) passes round the pulleys and effort is applied at the free end.

In practice, the pulley wheels in each block are mounted side by side on a common axle and are of same size; in Fig. 4.27 the pulleys are shown to be of varying sizes for convenience

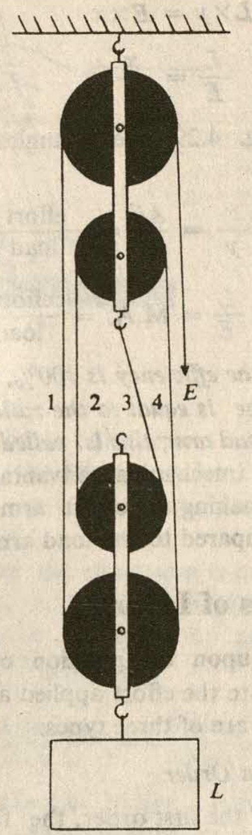


Fig. 4.27

to show how the rope passes than for the sake of reality. The fixed end of the rope is tied to the lower or the upper block depending upon whether the number of pulleys is odd or even, respectively.

When the number of pulleys is 4 (Fig. 4.27), for the load to be raised up through a distance of y, the four sections of the rope connecting the two blocks will have to be shortened by a distance of y each; hence the effort will have to move through a distance of $4y$. In other words, V.R. = 4.

Similarly, in the case of 5 pulleys, the effort will have to move through a distance of $5y$ when the load and lower block are raised through a height of y, see Fig. 4.28. In general, if the number of sections of the rope which support the lower block is n, the V.R. is also n. Since the efficiency is always less than 1,

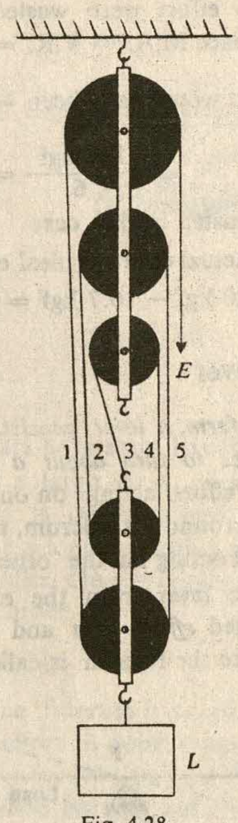


Fig. 4.28

M.A. < V.R. However, in general, the M.A. increases with increase of V.R. In practice, a limit on the number of pulleys is imposed by the increasing weight of the pulleys in comparison to the load.

EXAMPLE 4. A block and tackle of six pulleys is used to lift a load of 100 kgf with an effort of 20 kgf. Find its efficiency and also find how much of its effort is wasted.

$$\text{Mechanical advantage, M.A.} = \frac{\text{load}}{\text{effort}} = \frac{100 \text{ kgf}}{20 \text{ kgf}} = 5$$

$$\text{Velocity ratio, V.R.} = \text{number of pulleys } n = 6$$

Hence,

$$\text{Efficiency } \eta = \frac{\text{M.A.}}{\text{V.R.}} = \frac{5}{6} = 0.83 = 83\%$$

Ideally, if no effort were wasted, efficiency would be 1; hence M.A. = V.R. = 6.

Then, the effort would have been $= \frac{\text{load}}{\text{M.A.}}$

$$= \frac{100\text{ kgf}}{6} = \mathit{16.7\ kgf}$$

Hence effort wasted in this case

$$= \text{actual effort} - \text{ideal effort}$$

$$= 20\text{ kgf} - 16.7\text{ kgf} = \mathit{3.3\ kgf}$$

4.19 The Lever

In its simplest form, a lever consists of a rigid bar which is free to turn about a pivot called fulcrum. The effort acting on one side of the bar turns it around its fulcrum, and raises or moves the load acting on the other side. The portion of the lever from the effort to the fulcrum is called *effort arm* and the portion from the load to the fulcrum is called *load arm.*

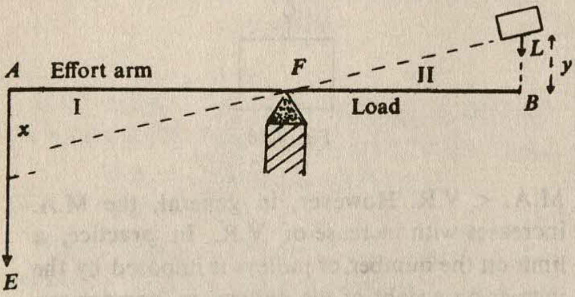


Fig. 4.29

In Fig. 4.29, AB is a lever which turns about the fulcrum F. When the effort is applied at A through a vertical distance x, the load at B is raised through a vertical height y. Then,

Output energy = load × distance moved by the load $= L \times y$

Input energy = effort × distance moved by the effort $= E \times x$

$$\text{Efficiency } \eta = \frac{\text{output energy}}{\text{input energy}}$$

$$= \frac{L \times y}{E \times x} = \frac{\text{M.A.}}{\text{V.R.}}$$

If the efficiency is assumed to be 100%,

$$L \times y = E \times x$$

or, $$\frac{L}{E} = \frac{x}{y}$$

From Fig. 4.29, the triangles I and II are similar.

Therefore $$\frac{x}{y} = \frac{AF}{BF} = \frac{\text{effort arm}}{\text{load arm}}$$

Hence, $$\frac{L}{E} = \text{M.A.} = \frac{\text{effort arm}}{\text{load arm}}$$

Thus, when the efficiency is 100%, the mechanical advantage is equal to the ratio of the effort arm to the load arm; this is called the Law of Levers. The mechanical advantage can be increased by making the effort arm as large as possible compared to the load arm.

4.20 Kinds of Levers

Depending upon the position of the fulcrum with respect to the effort applied and load overcome, levers are of three types:

Lever of First Order

In a lever of the first order, the fulcrum is in between the load and the effort (Fig. 4.30) as

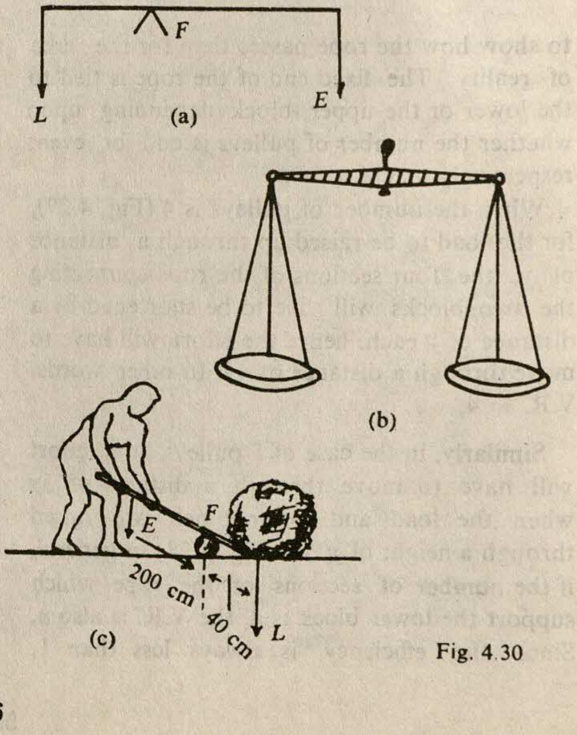
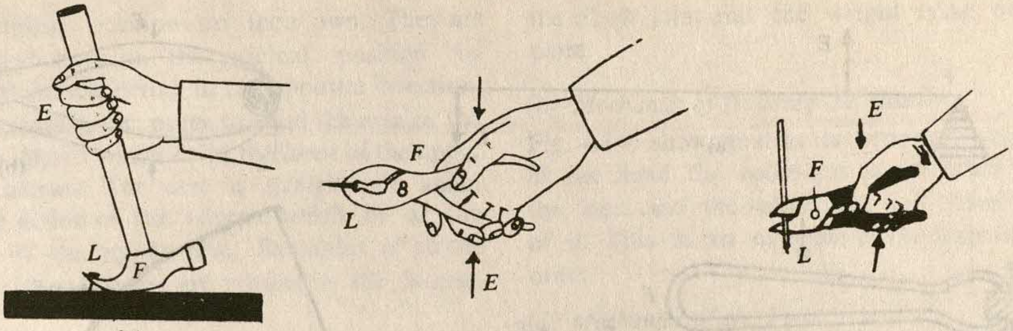


Fig. 4.30



(a) (b) (c)

Fig. 4.31

is the case of a beam balance and crow-bar. In a beam balance, the effort and load arms are equal and M.A. is equal to 1, provided the efficiency is 100%.

In a crow-bar the effort arm is bigger than the load arm, hence M.A. is more than 1 and a greater load can be overcome by applying a smaller effort. In Fig. 4.30c,

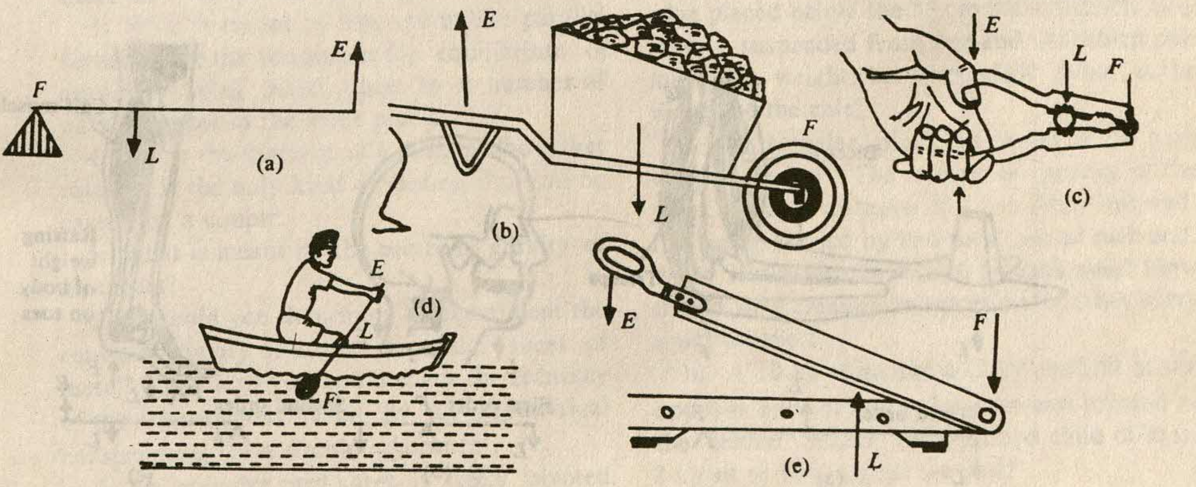
$$\text{M.A.} = \frac{\text{effort arm}}{\text{load arm}} = \frac{200 \text{ cm}}{40 \text{ cm}} = 5$$

Hence, with an effort of 20 kgf, a load of 100 kgf is overcome. Other examples of lever of the first order are claw hammer, a pair of pliers and cutting shears (Fig. 4.31a, b, c).

Shears for cutting metal sheets have long handles to obtain a greater mechanical advantage. Paper shears have short handles and long blades, because a large M.A. is unnecessary and the cutting is quicker; such shears gain speed by making a long cut with a short movement of the handles. Give two other examples of levers of first order.

Lever of Second Order

In this case, the fulcrum is at one end of the lever and the effort is applied near the other end, the load is in between the two (Fig. 4.32a). Examples are, wheel barrow, nut cracker, rowing of a boat and a paper cutter (Fig. 4.32b, c, d, e). In this type of lever, the effort arm is bigger than the load arm, so that a greater load is overcome by applying a smaller effort (Fig. 4.32a). Name two other examples.



(a) (b) (c) (d) (e)

Fig. 4.32

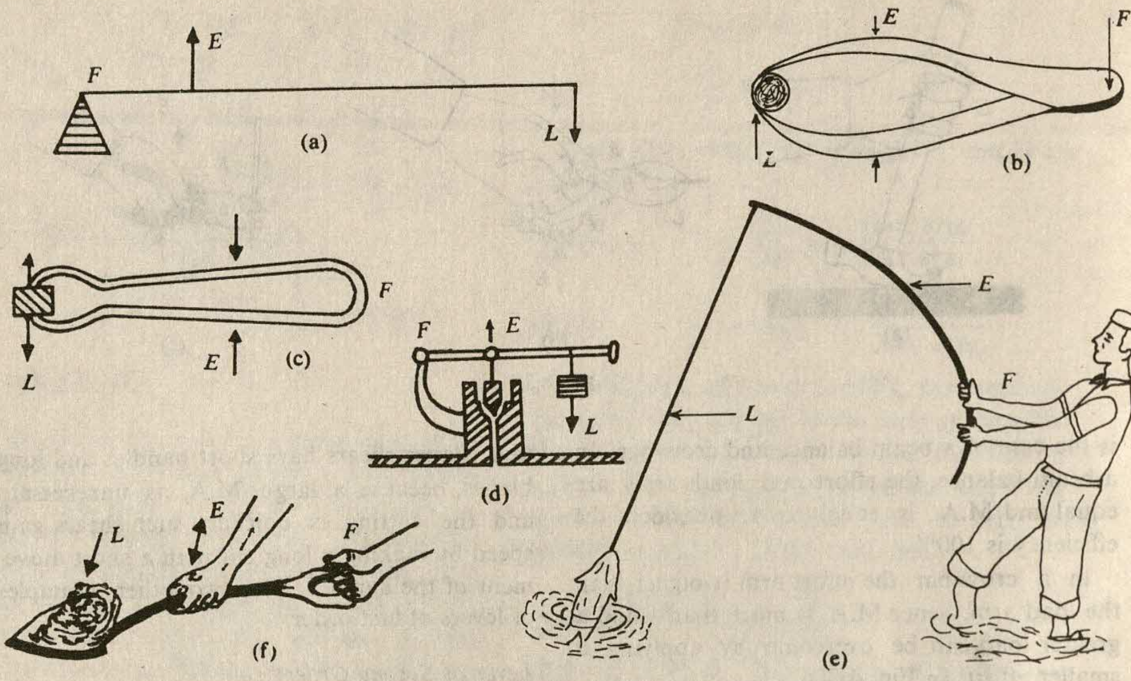


Fig. 4.33

Lever of Third Order

In this type of lever (Fig. 4.33a), the effort is applied in between the load overcome and the fulcrum, as in forceps, sugar tongs, safety valve, fishing rod and a spade used for shovelling coal (Fig. 4.33b, c, d, e, f). Hence the load arm is longer than the effort arm, so that a greater effort is needed to overcome a small load. In a forceps, a greater effort is used in lifting a small weight.

4.21 Physical Principles in Body Mechanics

Muscles in the human body exert force by contraction. However, they cannot come back to

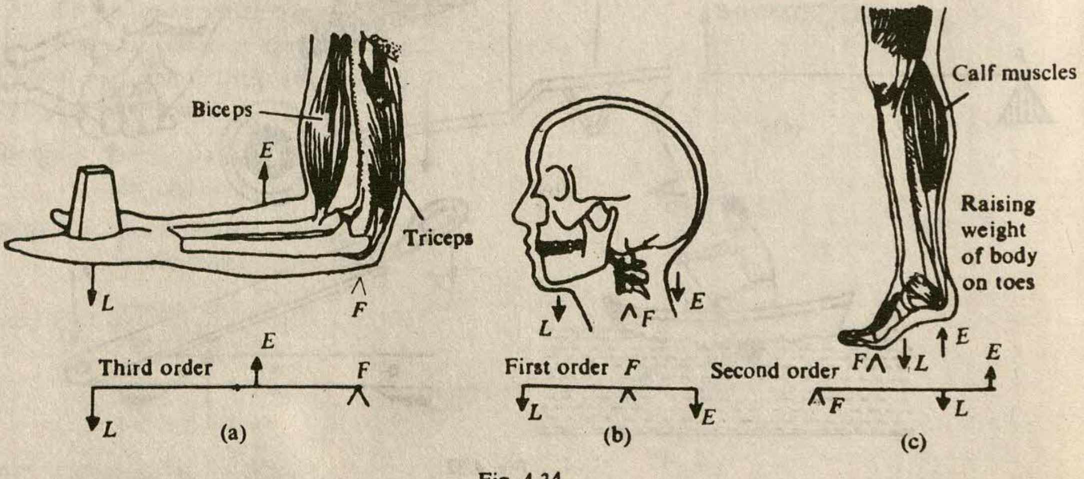


Fig. 4.34

the original position on their own. They are stretched back to the original position by another muscle acting in the opposite direction. For example, in order to bend the arm or the elbow, *biceps* which lie in the front of the upper arm contract. The arm is straightened again by the action of the triceps which lie at the back of the upper arm. Examples of all the three types of levers are present in the human body.

(a) *Mechanics of the Hand*

Fig. 4.34a shows that in raising a weight kept on a hand, the forearm acts as a lever of the *third order*. The elbow joint acts as a fulcrum, biceps exert the effort which lies between the elbow joint and the weight lying on the palm.

(b) *Mechanics of Nodding the Head*

Fig. 4.34b shows that in the action of nodding of the head the spine acts as a fulcrum while the load and the effort act on either side of it. This is an example of the lever of first order.

(c) *Mechanics of the Foot*

Figure 4.34c is the diagram of the lower leg and foot showing how the weight of the body is raised on the toes. This is an example of the lever of second order.

QUESTIONS

1. Explain why (a) it is easier to unscrew a nut with a wrench having a long handle; (b) it is difficult to open a door by applying a force near the hinges.

What is meant by the moment of a force about a point? In what units is it expressed?

2. How would you use a metre rule, a mass of 100 g and some thread to find out the mass of (a) the metre rule; and (b) of a metal piece? State the Principle of Moments.

3. What is meant by like and unlike parallel forces? State the conditions for equilibrium of an object being acted upon by a number of parallel forces in the same plane.

4. Define the moment of a couple. Show that rotation is the only kind of motion that can be caused by a couple.

5. What is meant by the centre of gravity of an object?

How would you determine by experiment the centre of gravity of a thin triangular sheet of metal? Show how you could check the accuracy of the experimental result by (a) geometrical construction, (b) a simple experiment.

6. An irregular card sheet is freely pivoted near one corner. Explain why the centre of gravity must lie vertically below the pivot when the sheet is in equilibrium.

7. A board is sloping at an angle of 30° to the horizontal. A block of wood is standing on it and is just at the point of toppling over. Draw a diagram of the system and mark on it the position of centre of gravity of the block. Show by an arrow how the pull of the earth acts on the block through its centre of gravity.

8. A uniform metre rule balances on a knife-edge placed below the 58 cm mark when a 20 g mass is suspended from one end. At which end must the weight be suspended? What is the weight of the rule?

9. An irregular plank of wood 4 m long weighs 16 kgf. The centre of gravity of the plank is at a distance of 1.5 m from one end. It is being carried by two men, one at each end. What is the weight carried by each man? How should they arrange distances so that they carry equal weights?

10. A 10 kg child and a 12 kg child sit at the opposite ends of a 4 m long see-saw pivoted at the centre. Where must a third child of mass 8 kg sit to balance the see-saw?

11. Explain what is meant by stable, unstable

and neutral equilibrium. Give two examples of each to illustrate your answer with diagrams.

12. State whether the following are in the state of stable, unstable or neutral equilibrium: (a) a wooden sphere placed on a table; (b) a funnel resting on its stem; (c) a player in the position of kicking a football.

13. Why are standing passengers not allowed on the upper deck of a double-decker bus?

Explain how the stability of a double-decker bus is affected by (a) the position of its centre of gravity; (b) width of the wheel base.

14. What is a machine? What is its purpose?

15. What is meant by mechanical advantage, velocity ratio and efficiency of a machine? Derive the relation between them taking the example of a pulley system or a lever.

16. What is meant by the statement: efficiency of a machine is 80%? Why is the efficiency of a machine less than 1?

17. In what way is a machine having a mechanical advantage less than 1 useful? Give two examples of such a machine.

18. Draw a diagram of a single string pulley system with a velocity ratio of (a) 3, (b) 6, (c) 5.

19. How does the efficiency of a pulley system change with the load applied? Explain with reason.

20. Show how a single pulley can be used to reduce the force required to overcome a given load. Show by a diagram that it is generally more convenient to use one more pulley.

If this two pulley system is used with an increased load, how will this affect (a) velocity ratio, (b) mechanical advantage, (c) efficiency of the system?

21. Describe the principle of the action of a simple lever. In an ordinary water pump, the lever is bent at an angle at the fulcrum and the end near the handle is heavy. What advantage is gained by this?

22. Explain (a) scissors for cutting cloth have blades longer than the handles while shears for cutting metal have blades shorter than the handles; (b) a nut can be cracked more easily with a nut cracker than with the fingers.

23. What do you mean by a faulty balance? How can you find the true mass of an object with a faulty balance having:

(i) pans of unequal weights.
(ii) arms of unequal lengths and pans of unequal weights.

5

Pressure and Archimedes' Principle

The word 'pressure' is commonly used in various contexts like 'political pressure', 'pressure of work' and blood pressure. People living in top stories of tall buildings often complain that water in their taps does not come with enough pressure. The word pressure in science has a definite meaning and is responsible for the flow of fluids—liquids and gases—which flow from higher to lower pressure.

5.1 What is Pressure?

Flat-footed camels are well suited for deserts and heavy tractors are able to negotiate marshy land, while swift horses are unable to do so. In order to explain these and many other observations, let us understand the meaning of pressure.

Activity 1. Press both ends of a drawing pin on your finger. It is observed that pressing the sharp edge is painful while the blunt edge is not. On pressing hard a mark is left on the skin by the sharp end. This is explained by saying that pressure exerted by the sharp end of fine area is much more than that by the flat end of large area and it increases by applying greater force.

The three quantities, pressure, force and area are related in a simple way as under:

$$\text{Pressure (N/m}^2\text{)} = \frac{\text{Force exerted normally (N)}}{\text{Area (m}^2\text{)}}$$

Pressure ***is defined as thrust or the force acting normally per unit area.***

EXAMPLE 1. A brick weighs 2.5 kg and measures 20 cm × 10 cm × 5 cm. Calculate the pressure exerted by it when it is lying flat and when it is standing on one end ($g = 10\ \text{m/s}^2$).

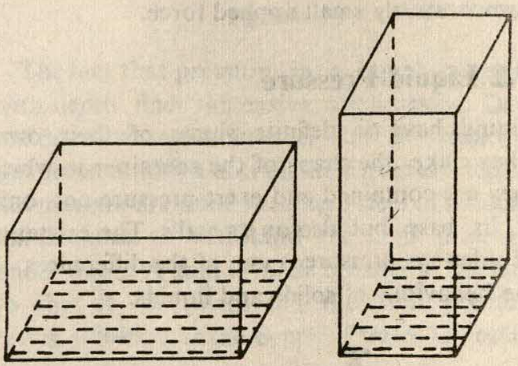


Fig. 5.1

Given Force exerted by brick $= mg = 2.5 \times 10$

$= 25\ \text{N}$

Area when lying flat $= 0.20 \times 0.10$

$= 0.02\ \text{m}^2$

Area when standing on

end $= 0.10 \times 0.05$

$= 0.005\ \text{m}^2$

To find Pressure $P_1 = ?$

$P_2 = ?$

Solution

Since $P = \dfrac{F}{A}$

$$\therefore \quad P_1 = \frac{25}{.02} = 1250 \text{ N/m}^2 \quad \textit{Answer}$$

and
$$P_2 = \frac{25}{.005} = 5000 \text{ N/m}^2 \quad \textit{Answer}$$

It is clear from the examples that smaller the area, more is the pressure. This explains why flat-footed camels can walk easily in sandy deserts while horses cannot. Since the area of the camel's feet is much more than that of a horse, the pressure exerted by a camel on the sand is less so that the camel sinks less in the sand. Heavy tractors can go through marshy land and muddy soil easily because their rear wheels have large area. The caterpiller tracks of tanks and huge excavators help them to negotiate any uneven and sinking ground because the pressure exerted on the ground is comparatively less. On the other hand, cutting and piercing tools like saws, needles and knives have sharp points or blades so that they exert great pressure with comparatively small applied force.

5.2 Liquid Pressure

Liquids have no definite shape of their own. They take the shape of the container in which they are contained and exert pressure not only at its base but also on its walls. The existence of sideways pressure is one of the differences in the behaviour of solids and liquids.

Activity 2. Take a polythene or tin container and make a few holes in it at different levels. Hold it under a tap of running water to fill it fully and then adjust the opening of the tap so that water maintains its level. You will observe that the pressure with which the water flows out increases according to the depth of the hole under the water surface (Fig. 5.2a). *The pressure in a liquid increases with depth.*

Now make some more holes in level with one of the existing holes and as before maintain the water level in the container. You will notice that the water flows out of these holes with equal pressure (Fig. 5.2). *Thus, at the same depth the pressure is the same in all directions.*

Activity 3. Take a U-tube half-filled with a liquid, say coloured water, and attach a thistle funnel to one of its limbs using a rubber tubing. Tie a thin rubber membrane tightly across the mouth of the funnel. The liquid stands at the same level in both the limbs. Slightly press the rubber membrane with your finger; the liquid level in the limb x falls and rises in the limb y. The difference of liquid levels in the two limbs gives the pressure exerted by the finger on the membrane. Press the membrane hard; the difference of levels becomes more. The U-tube containing liquid in its two limbs can serve as a pressure indicator and is called a *manometer* (Fig. 5.3). Three experiments can be performed

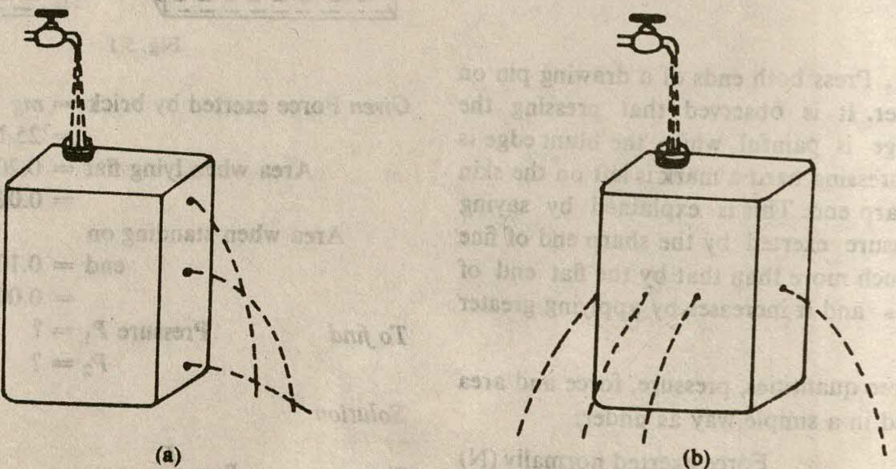


Fig. 5.2

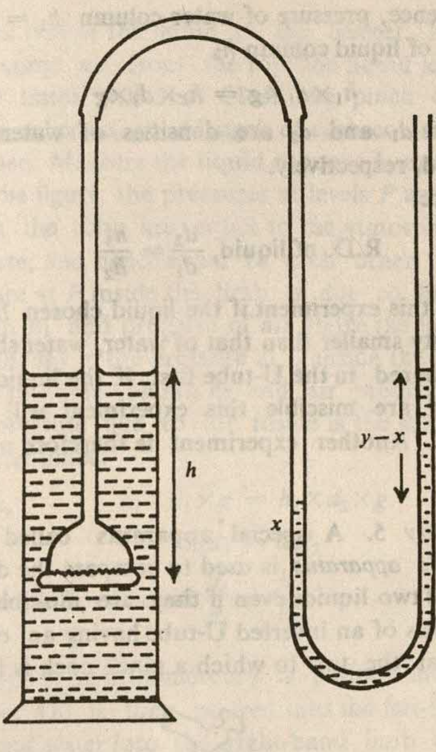


Fig. 5.3

with this pressure indicator to find out the dependence of pressure in a liquid on various factors.

Take a tall jar containing water and lower the funnel in it. As the funnel is lowered more and more, the level in x falls and that in y rises. This shows that the pressure inside a liquid increases with depth. It is found that on keeping the membrane at double the depth, the manometer gives double the difference of levels.

Hence, $P \propto h$ (depth)

Repeat the above experiment keeping the same level but taking a liquid of different density in the jar. The difference between x and y levels now alters. In the case of alcohol the difference of levels is about 0.8 times of that with water. As the density of alcohol is 0.8 g/cm^3, we can conclude that *the pressure exerted by a liquid column of a particular height is proportional to the density of the liquid.* Greater the density, more is the pressure.

Thus, $P \propto d$

or $P \propto hd$

or $P = hdg$ where g is a constant called acceleration due to gravity

or, Pressure, $P(\text{N/m}^2)$ = liquid column $h(\text{m}) \times$ density $(\text{kg/m}^3) \times$ constant $(9.8\ \text{m/s}^2)$

Keeping the centre of the membrane at the same horizontal level, repeat the experiment with the funnel pointing in different directions (Fig. 5.4). You will observe that the difference in x and y levels remains unchanged. *Thus at the same level within a liquid, pressure acts equally in all directions.*

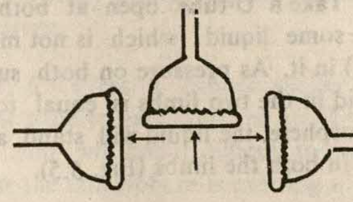


Fig. 5.4

The fact that pressure in a liquid increases with depth finds extensive applications. Deep sea divers wear a stout steel suit to withstand the pressure which acts on them at great depths. Submarines are built with hard steel of substantial thickness to withstand the high pressures under water. A dam is made broader at the base so that it can withstand the high pressure acting sideways as the depth of water increases.

EXAMPLE 2. Calculate the difference of pressure exerted by a column of mercury of height 76 cm and of sea water of depth 10 m (density of mercury = 13,600 kg/m^3; density of sea water = 1030 kg/m^3).

Given $h_1 = 0.76$ m

$d_1 = 13{,}600\ \text{kg/m}^3$

$h_2 = 10$ m

$d_2 = 1030\ \text{kg/m}^3$

To find $P_1, P_2 = ?$

Solution

Since $P = hdg$

$$\therefore \quad P_1 = 0.76\times 13{,}600\times 9.8$$
$$= 101{,}293 \simeq 1.01\times 10^5\,\text{N/m}^2$$

and
$$P_2 = 10\times 1030\times 9.8 = 100{,}940$$
$$\simeq 1.01\times 10^5\,\text{N/m}^2.$$

Thus the pressure exerted by 10 m of water is approximately the same as the pressure exerted by 76 cm of mercury which is the standard atmospheric pressure.

5.3 R.D. of Liquids by U-tube

A U-tube containing suitable liquid columns can be used to compare pressures of their columns and hence their densities.

Activity 4. Take a U-tube open at both ends and pour some liquid (which is not miscible with water) in it. As pressure on both surfaces of the liquid in the two limbs is equal to that of the atmosphere, the liquid will stand at the same level in both the limbs (Fig. 5.5).

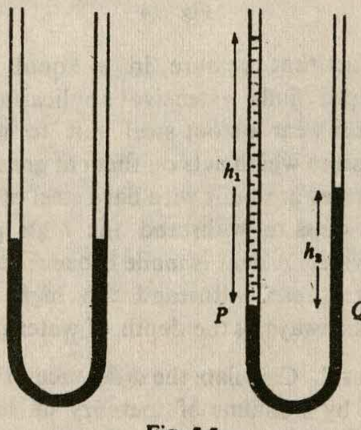


Fig. 5.5

Now pour water in one limb till the limb is almost full. The water column will push down the liquid in that limb. Consider the common level PQ of the liquid (Fig. 5.5). As pressure at the same level within the same liquid is equal,

Pressure at P = Pressure at Q

Pressure at P is due to the atmosphere and water column h_1; pressure at Q is due to atmosphere and liquid column h_2.

Hence, pressure of water column h_1 = pressure of liquid column h_2

or
$$h_1\times d_1\times g = h_2\times d_2\times g$$
where d_1 and d_2 are densities of water and liquid, respectively.

Hence,
$$\text{R.D. of liquid, } \frac{d_2}{d_1} = \frac{h_1}{h_2}$$

In this experiment if the liquid chosen has a density smaller than that of water, water should be poured in the U-tube first. If the liquid and water are miscible this experiment will not work. Another experiment is therefore necessary.

Activity 5. A special apparatus called the *Hare's apparatus* is used to compare the densities of two liquids even if they are miscible. It consists of an inverted U-tube having an opening at the top to which a pinch cock is fixed.

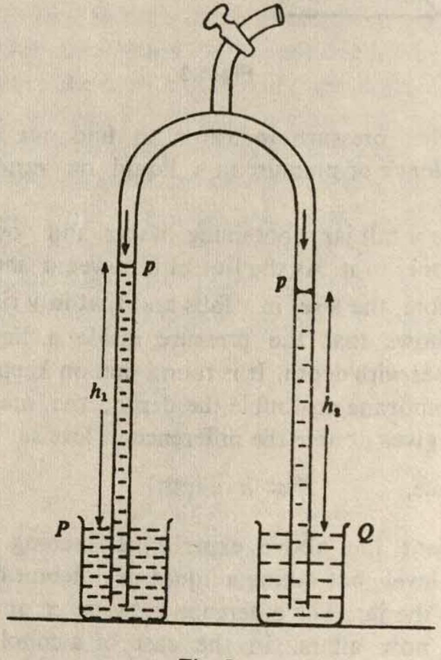


Fig. 5.6

The tube is mounted on a stand and its two limbs are inside the two liquids kept in beakers (Fig. 5.6). To start with, open the pinch cock; the liquid column in each limb will be at the same level as that of the liquid in the beaker. Now suck some air from the top; the liquid levels in the limbs will rise. Close the pinch cock tightly when a good length of each column is obtained. Measure the liquid columns h_1 and h_2.

In the figure, the pressures at levels P and Q within the tube are equal to the atmospheric pressure, and hence equal to each other. The pressure at P inside the limb is due to liquid column h_1 and pressure of air above the liquid column, say p; the pressure at Q inside the limb is due to liquid column h_2 and air pressure p The pressure due to air inside is the same in both the limbs.

Hence, $h_1 \times d_1 \times g = h_2 \times d_2 \times g$

or $h_1 d_1 = h_2 d_2$

Hence, R.D. of liquid $\frac{d_2}{d_1} = \frac{h_1}{h_2}$

Example 3. A little mercury is poured into a U-tube. Oil is than poured into the left-hand limb and water into the right-hand limb until the mercury stands at the same level in both the limbs. The length of oil and water columns is found to be 15 cm and 12 cm. Calculate the R.D. of the liquid and sketch the arrangement used.

Given Length of water column $h_1 = 12$ cm

Length of oil column $h_2 = 15$ cm

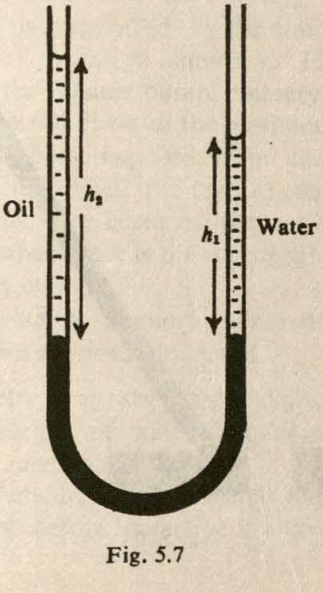


Fig. 5.7

To find R.D. of liquid $= \frac{d_2}{d_1} = ?$

Solution

$$\frac{d_2}{d_1} = \frac{h_1}{h_2} = \frac{12\text{ cm}}{15\text{ cm}} = 0.8$$

R.D. of liquid $= 0.8$

5.4 Atmosphere Exerts Pressure

Above the surface of the Earth, there is air upto 50 kilometres or so; it becomes rarer and rarer with altitude. The envelop of air that surrounds the surface of the Earth is called *atmosphere*. Air has weight and because of the weight of the air column acting per unit area, the atmosphere exerts pressure called *atmospheric pressure.*

Activity 6. Press a rubber sucker against a window pane to expel out the air. Try to pull it apart; you will find it difficult to do so. This is because the atmosphere is exerting a great force on its outer surface and there is no air inside it to neutralise it. This shows that the atmosphere exerts pressure.

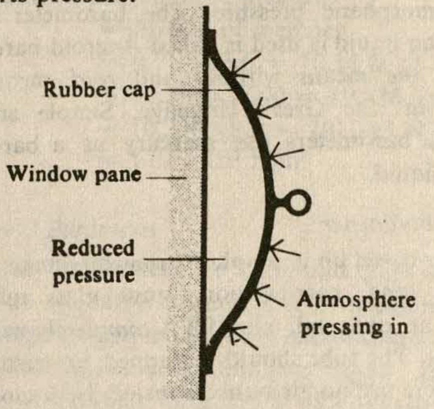


Fig. 5.8

The atmospheric pressure is about 1 kgf/cm^2 or 10 ton wt/m^2. The area of our body is about 2 m^2. This means that the atmosphere is exerting on us a force of about 20 ton wt. We move about without feeling it because the pressure of blood inside our body is slightly more than that of the atmosphere.

As we go up, the weight of air above becomes less and hence the atmospheric pressure decreases. Roughly the atmospheric pressure decreases by 1 cm of mercury after every 120 m of ascent in lower atmosphere. At higher altitudes, the nose may start bleeding because blood pressure is much more than the pressure outside.

Jet planes nowadays fly at an altitude of about 10,000 metres; there is so little air there that these planes are all 'pressuried' so that we can withstand the low pressure and also breathe normally. Our body is not suited to conditions of very low and very high pressures. Space travellers in satellites and those who landed on the Moon could come out of their vehicles only when they were wearing space suits which are 'pressuried' from inside.

Change of atmospheric pressure at a place caused wind movements. Meteorologists, who forecast weather, keep track of wind movements by gathering data on air pressure and other weather factors of a region; the information is plotted on special weather maps.

5.5 Barometers

Barometers are instruments which are used to find atmospheric pressure. The barometer in which no liquid is used is called Aneroid barometer; *Ane* means without and *roid* means liquid in the Greek language. Simple and Fortin's barometers use mercury as a barometric liquid.

Simple Barometer

In order to set up a simple barometer, take a 1 metre long, narrow bore stout glass tube closed at one end, and fill it *completely* with mercury. The tube should be tapped to ensure that there are no air bubbles inside. Now close the top end with a finger, carefully invert the tube so that the open end is inside a bowl of mercury, and gradually release the finger.

The mercury in the tube falls down slightly and settles at a certain level. Hold the tube vertical; the difference between the level of mercury in tube and in the trough gives the atmospheric pressure in terms of mercury column (Fig. 5.9). Atmospheric pressure acting on the surface of mercury in the bowl supports the column of mercury in the tube. The space above this column in the tube is a vacuum called *Torricellian vacuum*.

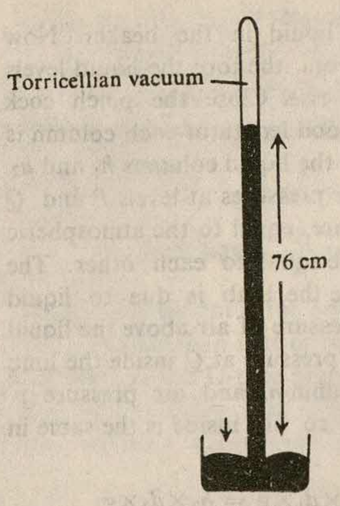


Fig. 5.9

In order to ensure that there is vacuum above mercury in the tube, it is lowered into the bowl containing mercury such that mercury in the tube reaches the top. If a 'metallic click' is heard, then the space above mercury was a vacuum, otherwise not. This is because if some air is present in the tube, it will serve as a cushion and the mercury will not strike against

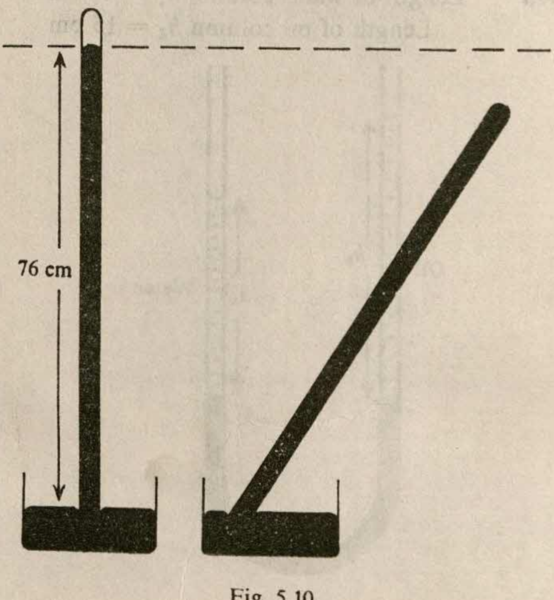


Fig. 5.10

the top and hence no metallic click will be heard. This can also be checked by tilting the tube such that the vertical height of the top of the tube above the mercury in the bowl or dish is less than the atmospheric pressure. If the tube gets completely filled with mercury, it shows that the space above the mercury was a vacuum, otherwise not; see Fig. 5.10.

In order to check that the space above the mercury is free of water vapour which is likely to be present if the mercury used is wet, the tube is lowered into the bowl. If waterdrops appear above the mercury, then water vapours were present otherwise not.

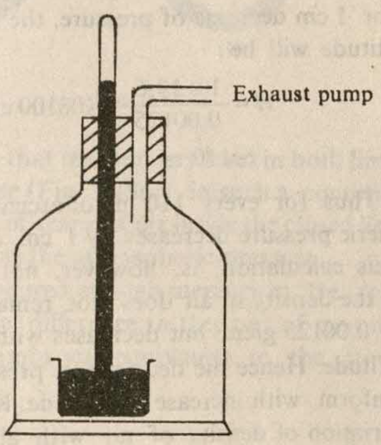


Fig. 5.11

In order to show that the mercury column in the tube is supported by the atmosphere, make the arrangement as shown in Fig. 5.11. On working the exhaust pump, mercury in the tube begins to fall down in the bowl and when all the air has been expelled from above the mercury in the bowl, the level of mercury in and outside the tube becomes the same. This shows that when there is no atmosphere, there is no mercury column.

In setting up a mercury barometer, the following precautions are observed:

1. The metre long tube must be dry to avoid the presence of water vapours in Torricellian vacuum.
2. The tube should be completely filled with mercury before inverting it to avoid the presence of any air in the space above mercury. Otherwise, because of the presence of air, the length of mercury column in the tube will be less.
3. The mercury should be pure and dry.
4. The tube should be held vertically, otherwise the pressure reading will be wrong.

It is advantageous to use mercury as a barometric liquid because (a) it is dense (R.D. is 13.6), hence a 1 m long tube is enough; (b) it is opaque and silvery in colour, so that its level can be read easily; (c) it does not stick to the walls of the container, hence accurate reading can be taken quickly; (d) it forms very little vapour so that above the mercury in the tube the vacuum is almost true and the reading is accurate.

The normal barometric pressure at sea level is found to support a column of 76.0 cm of mercury. Pressure also can be measured in terms of the column of mercury it can support; the normal pressure at sea level is therefore 76 cm of mercury.

Standard atmospheric pressure

$$\begin{aligned} &= 0.76 \text{ m of mercury} \\ &= 0.76 \times 13.6 = 10.34 \text{ m of water} \\ &= 10.336 \times 1000 = 10{,}336 \text{ kgf/m}^2 \\ &= 10{,}336 \times 9.8 = 101{,}293 \text{ N/m}^2 \\ &= 1.01 \times 10^5 \text{ N/m}^2 \end{aligned}$$

Aneroid Barometer

Mercury barometers are bulky and quite inconvenient to carry around. The most commonly used type of barometer is the *aneroid barometer*, so called because it contains no liquid. Essentially, it consists of a box *B* which is partially evacuated (Fig. 5.12). The top of this box is made of a thin metal so that it is sensitive to small changes in pressure. This small movement of the top of the box is 'magnified' by a series of levers and causes the pointer to move along a circular scale. The scale is graduated with a good mercury barometer. The scale is usually marked stormy, fair, etc. because changes in atmospheric pressure cause such changes in the weather.

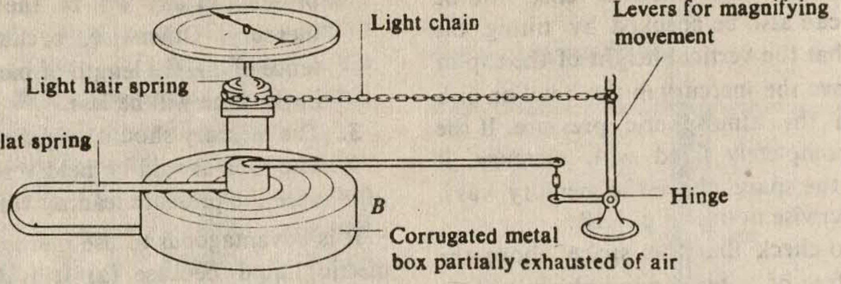

Light chain
Levers for magnifying movement
Light hair spring
Flat spring
Hinge
B
Corrugated metal box partially exhausted of air

Fig. 5.12

Aneroid barometers are also used as altimeters in aircrafts because increase of altitude is accompanied by decrease of atmospheric pressure; a fresh calibration of the scale is therefore sufficient to convert the instrument into an altimeter.

Uses of a Barometer

1. It is used in the laboratory to find atmospheric pressure.
2. It is used in the forecasting of weather. High pressure is associated with fine weather, while low pressure indicates unsettled weather. The fall of pressure shows presence of more water vapours in the atmosphere or that it is about to rain. Sudden fall of pressure is the forerunner of an incoming storm.
3. As an object goes up in the air, the weight of the air column above it becomes less. As the weight per unit area is the pressure, we can conclude that atmospheric pressure decreases with increase in altitude.

We know that at sea level atmospheric pressure is 76 cm of mercury. At a height of H cm, let the atmospheric pressure be p cm of mercury.

Decrease of pressure

$$= (76 - p) \text{ cm of mercury}$$
$$= (76 - p) \times 13.6 \text{ gf/cm}^2$$

Pressure of H cm of air cut off

$$= H \times \text{density of air}$$
$$= H \times 0.00125 \text{ gf/cm}^2$$

As decrease of pressure is due to H cm air column cut off, therefore,

$$H \times 0.00125 = (76 - p)13.6$$

or
$$H = \frac{(76 - p)13.6}{0.00125} \text{ cm}$$

For 1 cm decrease of pressure, the height H or altitude will be

$$H = \frac{1 \times 13.6}{0.00125} = 108100 \text{ cm}$$
$$\simeq 110 \text{ m}$$

Thus for every 110 m of ascent the atmospheric pressure decreases by 1 cm of mercury. This calculation, is, however, not strictly true as the density of air does not remain constant at 0.00125 g/cm^2 but decreases with increase in altitude. Hence the decrease in pressure is not uniform with increase in altitude. Knowing the variation of density of air with altitude, it is possible to calculate the height by measuring air pressure at that height. An aneroid barometer can thus be used as an **altimeter** (an instrument that measures altitude) by suitably caliberating the scale.

5.6 Boyle's Law

Gases have no fixed volume of their own; they occupy the volume of the vessel in which they are contained. However, unlike solids and liquids, their volume can be easily changed by altering the pressure applied. The relationship between volume and pressure was first investigated by Robert Boyle.

In this investigation, he assumed that the temperature remained unchanged throughout the experiment. He used a large J-shaped glass tube having its shorter arm closed. Enough mercury was added into the tube and the tube

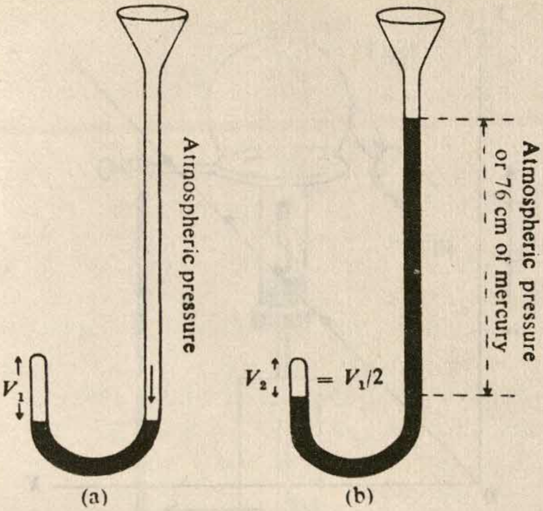


Fig. 5.13

was tilted so that the mercury level in both limbs was the same (Fig. 5.13a); in such a condition the pressure of trapped air inside the closed limb is the same as the atmospheric pressure.

He then poured enough mercury in the long limb till the difference in the level of mercury in the two limbs was equivalent to the atmospheric pressure (Fig. 5.13b); thus, pressure at the common level *PQ* in each limb was equal to *two* atmospheres. He observed that the volume of air trapped became half of the original volume. (Actually, Boyle found the length of air column to be half and assumed that the tube had a uniform bore).

When the pressure was increased to thrice that of the atmosphere, the volume became one-third of the original volume.

Thus, voulme of air $V \alpha \frac{1}{\text{Pressure, } P}$

or $P \times V = \text{constant}$

Later experiments showed that all gases behave in the same way as air. The results may be expressed as **Boyle's Law** *which states that the volume of a given mass of gas is inversely proportional to the pressure, provided the temperature of the gas is kept constant.*

Boyle's Law Apparatus

In the laboratory the pressure-volume relationship of air is investigated by using the Boyle's Law apparatus with which readings for pressure

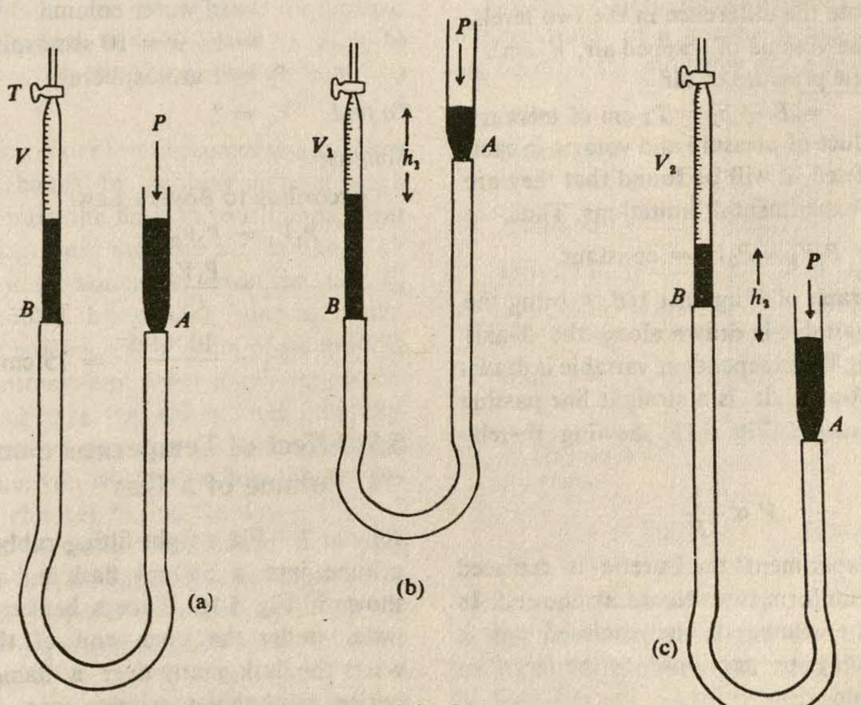


Fig. 5.14

both more and less than one atmosphere can be taken. The apparatus consists of a *burette* and a short glass tube connected by means of a rubber tubing and supported vertically on a stand (Fig. 5.14a). A scale is fixed between the two limbs. The burette is marked in cm^3 to read volume of air which is trapped when mercury is poured into the tube and the tap T is closed; in this condition the mercury level in the two limbs is the same and the pressure of trapped air is equivalent to that of the atmosphere. Let the volume and pressure of air be V cm^3 and P cm of mercury respectively.

Now raise the tube A; the mercury level in both the limbs rises but the level in A will be seen to be higher than that in B. Note the difference in the two levels h_1 cm, and the volume of air, V_1 cm^3. The air pressure is therefore h_1 cm of mercury in excess of atmospheric pressure.

Thus, new pressure of air

$$= P + h_1 \text{ cm of mercury} = P_1$$

Now lower the tube A sufficiently so that the mercury in both the limbs is seen to go down; however, the level in tube A is lower than that in tube B. Note the difference in the two levels, h_2 cm, and the volume of trapped air, V_2 cm^3.

Hence, new pressure of air

$$= P - h_2 = P_2 \text{ cm of mercury}$$

If the product of pressure and volume in each case is calculated, it will be found that they are equal within experimental limitations. Thus,

$$PV = P_1V_1 = P_2V_2 = \text{constant.}$$

Draw a graph of V against $1/P$. V being the dependable variable is drawn along the Y-axis and $1/P$ being the independent variable is drawn along the X-axis. It is a straight line passing through the origin (Fig. 5.15) showing thereby that

$$V \propto \frac{1}{P}$$

In some experiments the burette is replaced by a plain uniform tube closed at one end. In such cases the volume of the enclosed gas is taken as being proportional to the *length* of the air column.

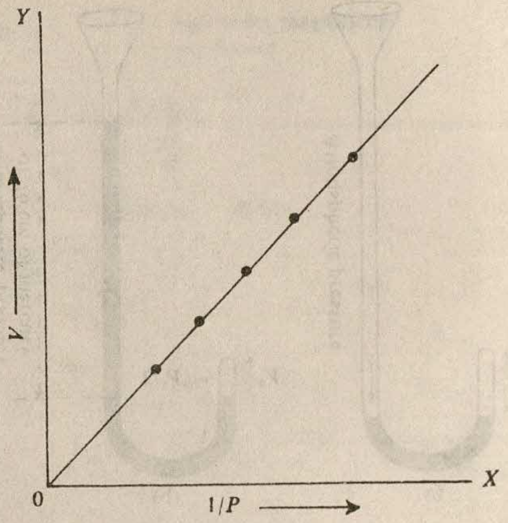


Fig. 5.15

EXAMPLE 4. An air bubble at the bottom of a lake 90 m deep has a volume of 1.5 cm^3. What will be its volume just below the surface if the atmospheric pressure is equivalent to a height of 10 m of water.

Given $V_1 = 1.5$ cm^3

P_1 = atmospheric pressure + pressure of water column

$= 1 + 9 = 10$ atmospheres

$P_2 = 1$ atmosphere

To find $V_2 = ?$

Solution

According to Boyle's Law:

$$P_1V_1 = P_2V_2$$

or

$$V_2 = \frac{P_1V_1}{P_2}$$

$$\therefore \quad V_2 = \frac{10 \times 1.5}{1} = 15 \text{ cm}^3$$ *Answer*

5.7 Effect of Temperature on Volume of a Gas

Activity 7. Fix a tight-fitting rubber cork and a tube into a 500 ml flask and support it as shown in Fig. 5.16. Place a beaker filled with water under the open end of the tube and warm the flask gently over a flame. You will notice air bubbles coming out of the water

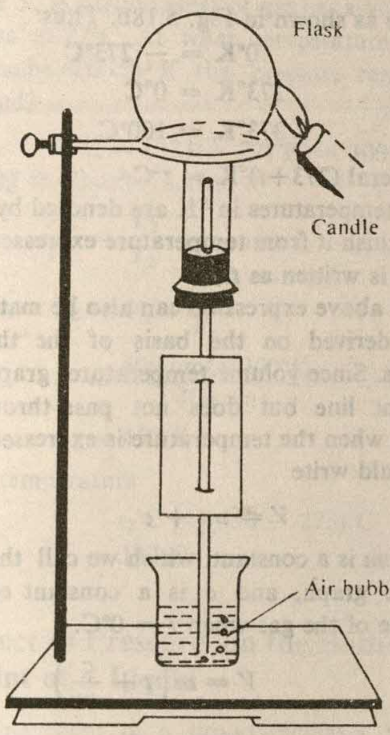


Fig. 5.16

showing thereby that air expands on heating. Now allow the flask to cool. Water is seen to rise up the tube; this shows that air contracts on cooling.

Wait till the water level becomes steady. Now warm your hands by rubbing against each other and grasp the flask in your hands. Heat from your hands expands the air in the flask and forces water noticeably down the tube. If the flask is cooled by passing running water over it or by holding a few cubes of ice around it, the air contracts and water level rises up the tube. If you observe the water level carefully against a scale held next to it over a large period of time, you will realise how the temperature of air changes during the day.

We have actually constructed a simple thermometer to record atmospheric temperature changes. It will have to be caliberated first in comparison to a standard thermometer before it can be used.

It has been studied earlier that the volume of a gas and its pressure depend upon its temperature. Thus temperature, pressure and volume of a gas are interdependent variables, and a relationship between any two variables can be established through suitable experiments. Investigations lead to the following laws:

(i) Boyle's Law

The volume of a fixed mass of gas varies inversely as its pressure if the temperature is unchanged. Mathematically

pressure × volume = constant.

(ii) Charles' Law

Activity 8. Take a 50 cm long uniform glass tube of 1 mm bore closed at one end. By slight heating and then cooling when the open end is dipped in mercury, a small pellet of mercury can be drawn in the tube up to the middle. The pellet serves to trap a small quantity of air in the tube which is kept separated from the atmosphere by the pellet. The pellet also serves to maintain a constant pressure on the enclosed air which is equal to the outside pressure plus the pressure of the pellet column.

The tube is fixed vertically in a tall jar containing water or a suitable liquid of high boiling point. A thermometer and a scale are also fixed close to the tube (Fig. 5.17). At successive steady temperatures of the oil, the length of air column trapped is recorded. For example a lot of ice can be added to bring the temperature to 0°C.

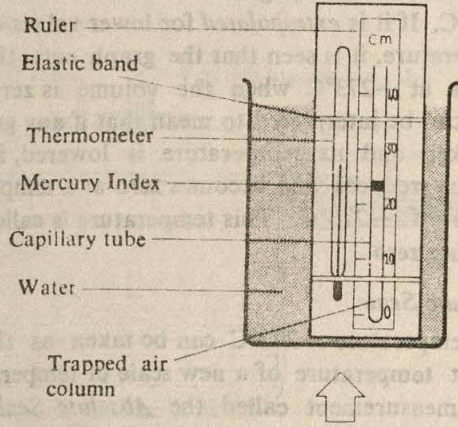


Fig. 5.17

A graph of length of air column against the temperature in °C is plotted. Since length of air column in a tube of uniform cross-section is proportional to its volume, the length-temperature graph is equivalent to a volume-temperature graph for the fixed mass of gas (Fig. 5.18a).

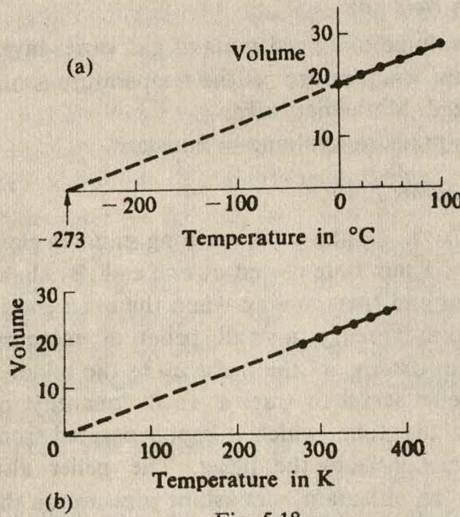


Fig. 5.18

The graph is a straight line; this shows a linear relationship between volume of a gas and its temperature read in °C. However, the graph shows that the gas has a finite volume at 0°C. If it is *extrapolated* for lower values of temperature, it is seen that the graph cuts the X-axis at -273°C when the volume is zero. This can be interpreted to mean that if any gas is taken and its temperature is lowered, its volume reduces and becomes zero at a temperature of -273°C. This temperature is called **absolute zero.**

Absolute Scale

The temperature -273°C can be taken as the lowest temperature of a new scale of temperature measurement called the *Absolute Scale.* This lowest temperature is marked as 0°K.

The degree intervals are however taken to be the same as for the Celcius scale. Thus, there will be 100 degree between the melting point of ice and the boiling point of water on this scale. A new graph showing the relationship between volume and temperature of the gas will be as shown in Fig. 5.18b. Thus:

$$0°\text{K} = -273°\text{C}$$
$$273°\text{K} = 0°\text{C}$$
$$373°\text{K} = 100°\text{C}$$

In general $(273+t)°\text{K} = t°\text{C}$

All temperatures in °K are denoted by T to distinguish it from temperature expressed in °C which is written as t.

The above expression can also be mathematically derived on the basis of the theory of graphs. Since volume-temperature graph is a straight line but does not pass through the origin when the temperature is expressed in °C, we could write

$$V = mt + c$$

where m is a constant, which we call the slope of the graph, and c is a constant equal to volume of the gas when $t = 0$°C.

$$\therefore \qquad V = m\left(t + \frac{c}{m}\right)$$

Experimentally we obtain $\dfrac{c}{m} = 273$

Hence, $\qquad V = m(t + 273)$

By changing the scale of measurement to Absolute Scale we write a general equation:

$$V = mT \quad \text{or} \quad \frac{V}{T} = \text{constant.}$$

Charles' Law *states that at constant pressure the volume of a fixed mass of gas is directly proportional to its absolute temperature. This is ideally true for all gases.*

(iii) Pressure Law

A similar experiment conducted by keeping the volume of a gas constant, and recording the dependence of its pressure on temperature shows that

$$P \propto T$$

or $$\frac{P}{T} = \text{constant.}$$

This is the *Pressure Law* which states that *the pressure of a fixed mass of any gas at constant volume is directly proportional to its absolute temperature.*

Example 5. A certain mass of gas has a volume of 400 cm^3 at 27°C. At what temperature will its volume be 600 cm^3 if the pressure remains unchanged?

Solution $27^\circ\text{C} = (273 + 27)^\circ\text{K} = 300^\circ\text{K}$

According to Charles' Law:

$$\frac{V_1}{T_1} = \frac{V_2}{T_2} = \text{constant}$$

Hence, $T_2 = V_2 \times \frac{T_1}{V_1}$

$$= \frac{600\ \text{cm}^3 \times 300^\circ\text{K}}{400\ \text{cm}^3}$$

$$= 450^\circ\text{K}$$

The new temperature

$$t_2^\circ\text{C} = (450 - 273)^\circ\text{C}$$

$$= 177^\circ\text{C}$$ *Answer*

5.8 Effect of Pressure on the Boiling Point of a Liquid

The boiling point of a liquid increases with increase of pressure. The boiling point of water at normal pressure of 76 cm of mercury is 100°C and it changes by 1°C for every 3 cm change in pressure.

Activity 9. Boil water in a strong round-bottomed flask. Allow steam to come out of its mouth freely and profusely for a minute or two. Remove the flame and close the mouth of the flask tightly with a cork carrying a thermometer. Invert the flask and support it in the position shown in Fig. 5.19.

When boiling stops, pour cold water on the inverted flask. You will observe that the boiling starts again. This may be repeated a number of times, and the water can be set to boil again even when the temperature is several degrees below 100°C.

The cold water condenses some of the steam present in the upper part of the flask and so reduces pressure on the warm water. This lowers the boiling point and water begins to boil at a temperature below 100°C. This type of experiment was first conducted by Franklin and is therefore called Franklin's experiment.

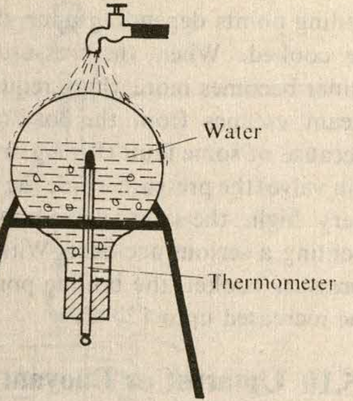


Fig. 5.19 Franklin's experiment

As the altitude increases pressure decreases, hence water at higher altitudes boils at lower temperatures. This is why it becomes difficult to cook meat and pulses at high altitudes.

5.9 The Pressure Cooker

The time taken in cooking vegetables and other foods can be reduced greatly by raising the boiling point of the water in which they are cooked. This can be achieved by raising the pressure. This is the principle of a **pressure cooker.**

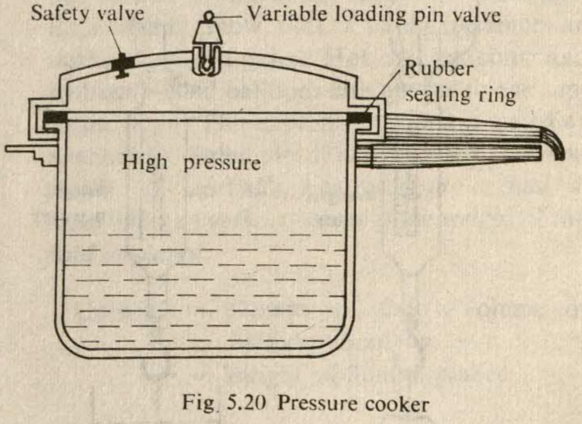


Fig. 5.20 Pressure cooker

It consists of a stout aluminium container fitted with a lid having a rubber sealing ring. With the variable loading pin valve different pressures can be applied to achieve different boiling points depending upon the vegetable to be cooked. When the pressure inside the container becomes more than required, the excess steam escapes from the loading pin valve. If because of some fault (for e.g. a blockage in the pin valve) the pressure inside the cooker becomes very high, the safety valve blows off, thus preventing a serious accident. With the help of the pressure cooker, the boiling point of water can be increased upto 120°C.

5.10 Upthrust or Buoyant Force

It is a common experience that if you try to push a plank of wood under water you find that the water also pushes the plank upwards. A boy jumping into water in a swimming pool quickly comes up to the surface.

Activity 10. **Tie a string around a stone or a lump of metal weighing about 400 gf and suspend it from a spring balance using a thin string. Record the weight of the solid (Fig. 5.21a). Now lower the solid gradually inside water contained in a large beaker.**

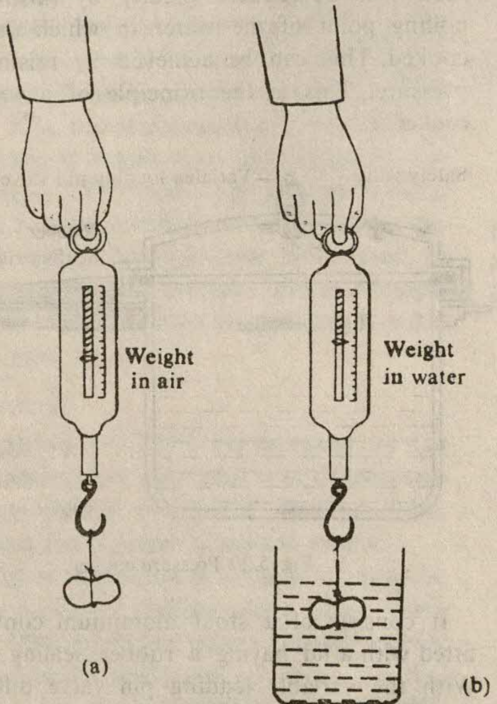


Fig. 5.21

You will observe that the balance records a lower weight (Fig. 5.21b). Since the pull of gravity on the solid can be considered to remain constant, the *apparent loss in weight* **can only be due to an upward force exerted by water on the solid.** *This upward force which a liquid exerts upon an object placed in it is called the* **bouyant force or upthrust.**

It is further noticed that the loss in weight increases as the solid is lowered more and more inside water till it is completely immersed. Once inside water, there is no further loss of weight whatever may be the depth of the solid below the surface of water so long as it does not rest on the bottom of the beaker. When half the volume of the solid is immersed, the loss in weight is noticed to be half, and so on. This shows that the upthrust is proportional to the volume of the solid inside the liquid. Hence

Upthrust $\propto$ Volume immersed

Activity 11. **Take two liquids of different densities in separate beakers; for example, oil of density 0.8 g/cm^3 and copper sulphate solution of density 1.2 g/cm^3. The solid is now completely immersed in them and the loss of weight recorded. It is observed that greater the density of the liquid, more is the loss in weight. The same solid immersed in oil, water and copper sulphate solution shows a loss in weight in the ratio of 0.8 : 1.0 : 1.2, respectively. Thus, the upthrust is proportional to the density of the liquid in which the solid is immersed. Hence**

Upthrust $\propto$ density of liquid

Therefore, Upthrust $\propto$ Density of liquid $\times$ Volume of solid immersed. Since the solid when immersed displaces liquid equal to its own volume,

Upthrust $\propto$ Density of liquid $\times$ Volume of liquid displaced

The numerical relationship between these quantities was given by Archimedes'

5.11 Archimedes' Principle

Archimedes' was a Greek scientist who lived

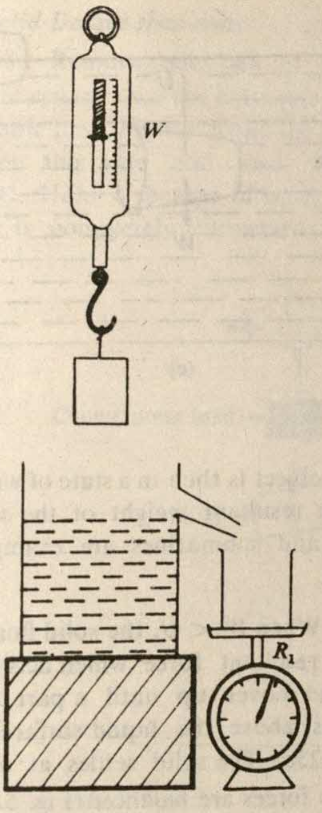


Fig. 5.22 (a)

nearly 2000 years ago. The law for which he is given credit is perhaps the first experimental conclusion known in science. Its importance can only be appreciated when we study the Principle and its numerous applications.

Activity 12. **Place an *overflow can* on a wooden block. Fill the can with water till it starts flowing out of its spout. Place an empty beaker on the pan of a compression balance and arrange it so that it is just under the spout (Fig. 5.22a). Record the weight of the beaker, R_1, and the solid hung in air from a spring balance, W.**

Now gradually lower the solid into the water in the can till it is completely immersed (Fig. 5.22b). Record the apparent weight W' of the solid as read in the spring balance, and the weight of the beaker plus the displaced water gathered in the beaker, R_2. It is noticed that the weight of water displaced ($R_2 - R_1$) is equal to the loss in weight ($W - W'$) which is due to the upthrust. R_1 and R_2 are the readings of the compression balance and W and W' are readings of spring balance.

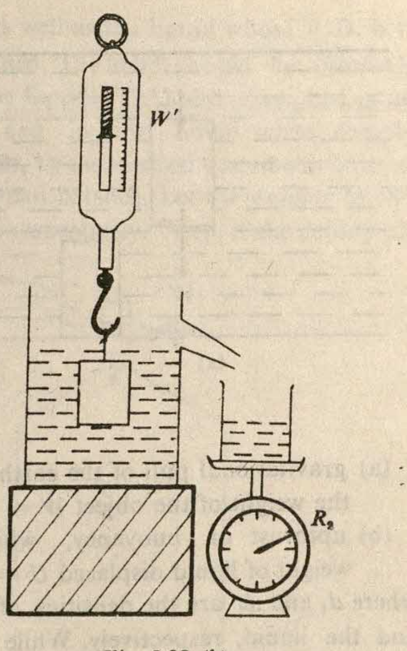


Fig. 5.22 (b)

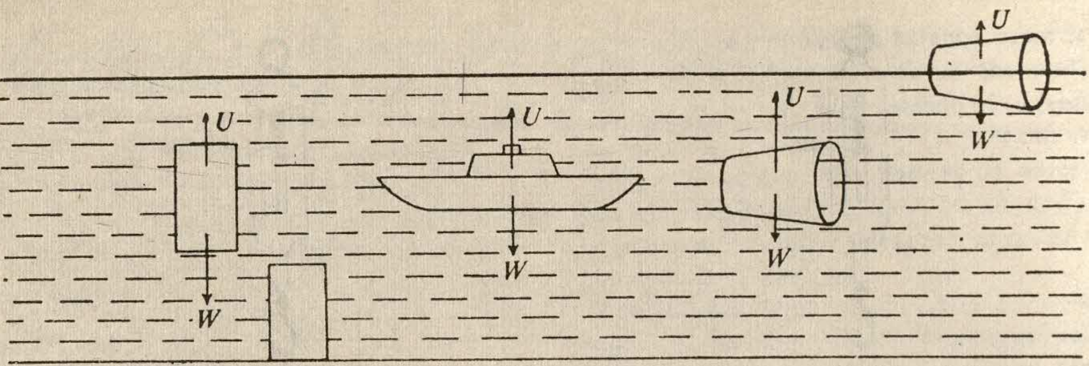
If the experiment is repeated using oil or copper sulphate solution instead of water, the loss in weight as well as weight of liquid displaced vary according to the density of the liquid, but the two quantities are equal in each case. Experiments show that a solid experiences an upthrust even in gases. Hot air balloons and hydrogen-filled balloons rise up due to the upthrust in air. This experimental fact is stated as **Archimedes' Principle**: *When an object is completely or partially immersed in a fluid, it experiences an upthrust equal to the weight of the fluid displaced.*

Upthrust = Density of fluid × Volume of fluid displaced × g

= Weight of fluid displaced

5.12 Floating and Sinking

When an object is immersed in a fluid partly or fully, two forces act on it:



(a) (b) (c) (d)

Fig. 5.23

(a) gravitational pull of the earth, which is the weight of the object $W = V \times d_1$

(b) upthrust or buoyancy, which is the weight of liquid displaced $U = V' \times d_2$

where d_1 and d_2 are the densities of the solid and the liquid, respectively. While the weight W acts vertically downwards, the upthrust U acts vertically upwards. As a result of these two forces acting on the solid, three cases arise:

(i) When the resultant downward force is positive or $W > U$ the solid sinks. As the solid is fully immersed inside the liquid (Fig. 5.23a), $V = V'$

Hence, resultant downward force

$$= W - U = V(d_1 - d_2)$$

Thus, for the resultant downward force to be positive, the density of solid d_1 should be greater than density of liquid d_2 and the solid will then sink. This resultant downward force which is equal to the weight of solid in the liquid is read by the spring balance in experiments described above.

(ii) When $W = U$, the two forces are balanced and if the solid is stationary it will stay in the position of rest completely immersed in the liquid. When the solid is completely immersed in a liquid (Fig. 5.23b), $V = V'$. In this case,

Resultant force $= 0$; $W = U$ or $V \times d_1 = V \times d_2$

Hence, when the density of the solid is equal to the density of the liquid, the solid remains floating completely immersed in the liquid.

The object is then in a state of weightlessness, i.e. the resultant weight of the object is zero. Fishes and submarines are examples of such objects.

(iii) When $W < U$, the solid floats. There is a net resultant force which acts upwards and the solid moves up until a part of the solid appears above the liquid surface and $V > V'$ (Fig. 5.23c). The solid settles at a level when the two forces are balanced (Fig. 5.23d). In this condition of equilibrium

$$W = U \text{ or } V \times d_1 = V' \times d_2$$

Since $\quad V > V', d_1 < d_2$

Thus, when the density of a solid is less than the density of the liquid, the solid floats on the surface of the liquid partly immersed in the liquid.

When immersed inside the liquid the object experiences an upward force and is consequently pushed up when released. For example, if we push a closed tin full of air into a liquid and release it, it is pushed up to the surface of the liquid.

5.13 R.D. by Archimedes' Principle

The above experiments leading to Archimedes Principle can be used for the determination of relative density of solids and liquids. A spring balance cannot read weights of objects very accurately; a beam balance is therefore generally used in such experiments.

R.D. of Solid Denser than water

Activity 13. Remove one pan of a physical balance and *counterpoise* the balance by suspending a suitable load. Now suspend the solid from a hook on this side and find its weight (Fig. 5.24). Hold a beaker of water such that the solid is completely immersed and not touching the sides of the beaker. The solid will now weigh less. Record the weight of the solid when immersed in water, W'

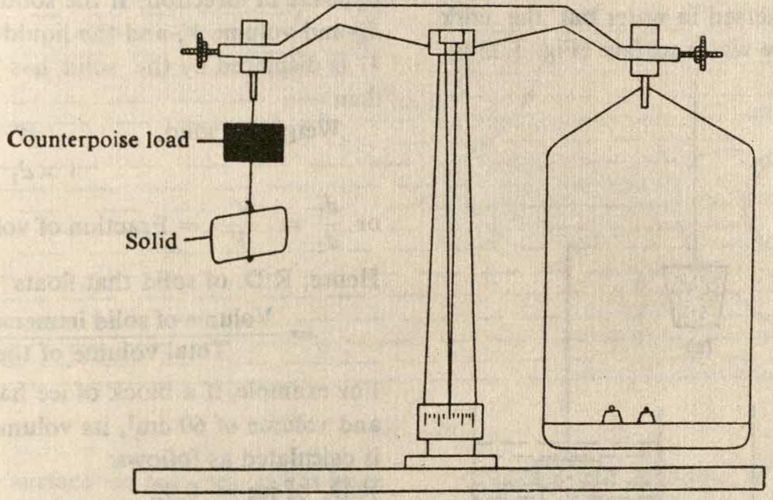


Fig. 5.24

Weight of the solid in air $= W = V \times d_1$

Loss in weight of solid $= W - W'$

$= \text{upthrust } U = V \times d_2$

$$\text{Hence, } \frac{W}{W - W'} = \frac{V \times d_1}{V \times d_2} = \frac{d_1}{d_2} = \text{R.D. of solid}$$

Thus, R.D. of solid

$$= \frac{\text{Weight of solid in air}}{\text{Loss of weight in water when fully immersed}}$$

For example, a solid of mass 400 g weighs 350 gf in water, then,

$$\text{R.D. of solid} = \frac{400 \text{ gf}}{(400 - 350) \text{ gf}} = 8.0$$

An extension of the experiment is to determine the R.D. of a liquid.

R.D. of Liquid

Activity 14. Take a solid which would sink in water as well as the liquid whose R.D. is to be determined. The solid should be insoluble in both the liquids. The solid is weighed in air, in water and in the liquid when completely immersed, by the method described above, using the one-pan balance. Let the weights be W, W' and W'', respectively. Then, if the density of the liquid is d_3, by Archimedes' Principle,

loss of weight in water $= W - W' = V \times d_2$

loss of weight in liquid $= W - W'' = V \times d_3$

$$\text{Hence, } \frac{W - W''}{W - W'} = \frac{V \times d_3}{V \times d_2} = \frac{d_3}{d_2} = \text{R.D. of liquid}$$

Thus, R.D. of liquid

$$= \frac{\text{Loss of weight of solid in liquid}}{\text{Loss of weight of same solid in water}}$$

For example, a piece of sealing wax weighs 27 gf in air and 12 gf in water. It is then weighed in a liquid of relative density 0.8 g/cm^3. The weight of wax in the liquid can be found out as follows:

R.D. of liquid

$$= \frac{\text{Weight in air} - \text{weight in liquid}}{\text{Weight in air} - \text{weight in water}}$$

$$\text{Hence, } 0.8 = \frac{27 \text{ gf} - W'' \text{ gf}}{27 \text{ gf} - 12 \text{ gf}} = \frac{27 - W''}{15}$$

$$0.8 \times 15 = 27 - W''$$

$$\text{Hence } W'' = 27 - 12 = 15 \text{ gf}$$

R.D. of Solid Less Dense than Water

Activity 15. Let us suppose that the R.D. of a piece of cork is to be determined. Use the one-pan physical balance and by the method described earlier find out the weight of the cork in air, W. Now tie a piece of metal, called a *sinker*, to the same thread just below the cork. Arrange the beaker of water so that the sinker is fully immersed in water but the cork is fully above the water surface (Fig. 5.25 b).

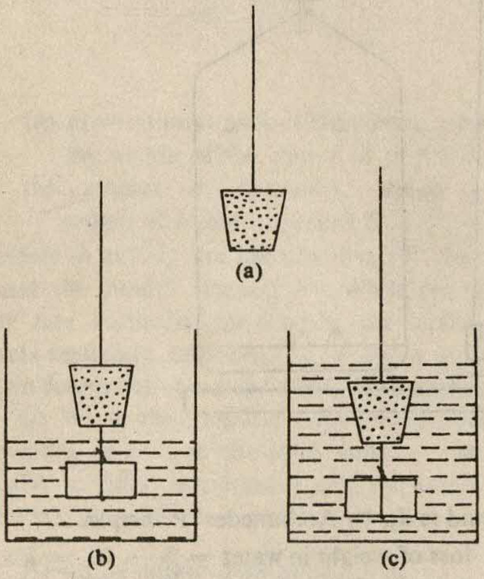


Fig. 5.25

Record the weight W_1. Now hold the beaker of water such that the sinker and the cork are fully immersed; it is possible for the cork to be fully immersed even if it is less dense than water because it is attached to the sinker (Fig. 5.25 c). The weight W_2 in this case will be less than W_1 due to the upthrust on the cork piece.

Let, weight of cork in air $= W$ gf

Weight of cork in air + sinker in water $= W_1$ gf

Weight of cork in water + sinker in water $= W_2$ gf

Hence, loss of weight of cork in water $= W_1 - W_2$

$$\text{Hence, R.D. of cork} = \frac{W}{W_1 - W_2}$$

5.14 Law of Floatation

It has been noted earlier that when an object has a density less than that of a liquid, it floats on the surface of the liquid. The solid displaces some liquid whose weight equals the upthrust. When the solid floats freely, its weight W and the upthrust U are equal in magnitude and opposite in direction. If the solid has a density d_1 and volume V, and the liquid whose volume V' is displaced by the solid has a density d_2, then

$$\text{Weight of solid,} \quad W = \text{Upthrust, } U$$

$$V \times d_1 = V' \times d_2$$

$$\text{or} \quad \frac{d_1}{d_2} = \frac{V'}{V} = \text{Fraction of volume immersed}$$

Hence, R.D. of solid that floats

$$= \frac{\text{Volume of solid immersed in water}}{\text{Total volume of the solid}}$$

For example, if a block of ice has R.D. of 0.92 and volume of 60 cm^3, its volume under water is calculated as follows:

$$\text{R.D. of ice} = 0.92$$

$$= \frac{\text{Volume immersed, } V'}{\text{Total volume, } V = 60 \text{ cm}^3}$$

Hence, volume of ice inside water

$$= 0.92 \times 60 \text{ cm}^3 = 55.2 \text{ cm}^3$$

$$= 55 \text{ cm}^3 \text{ approximately}$$

The fraction of volume above water surface,

$$= 1 - 0.92 = 0.08 \simeq 1/12$$

When a solid floats freely on a liquid, and its weight is balanced by the upthrust, its apparent weight is zero; the solid has lost all its weight. This fact is also stated as the **Law of Floatation**. The weight of a liquid displaced by a floating object is equal to the weight of the object, or a *freely floating object displaces weight of liquid equal to its own weight.*

Ships are so shaped that they are capable of displacing water equal to their own weight and that of all cargo and passengers. If an extra load is added, the ship sinks deeper so that additional water is displaced equal to the weight of the load.

A *submarine* can float on the surface as well

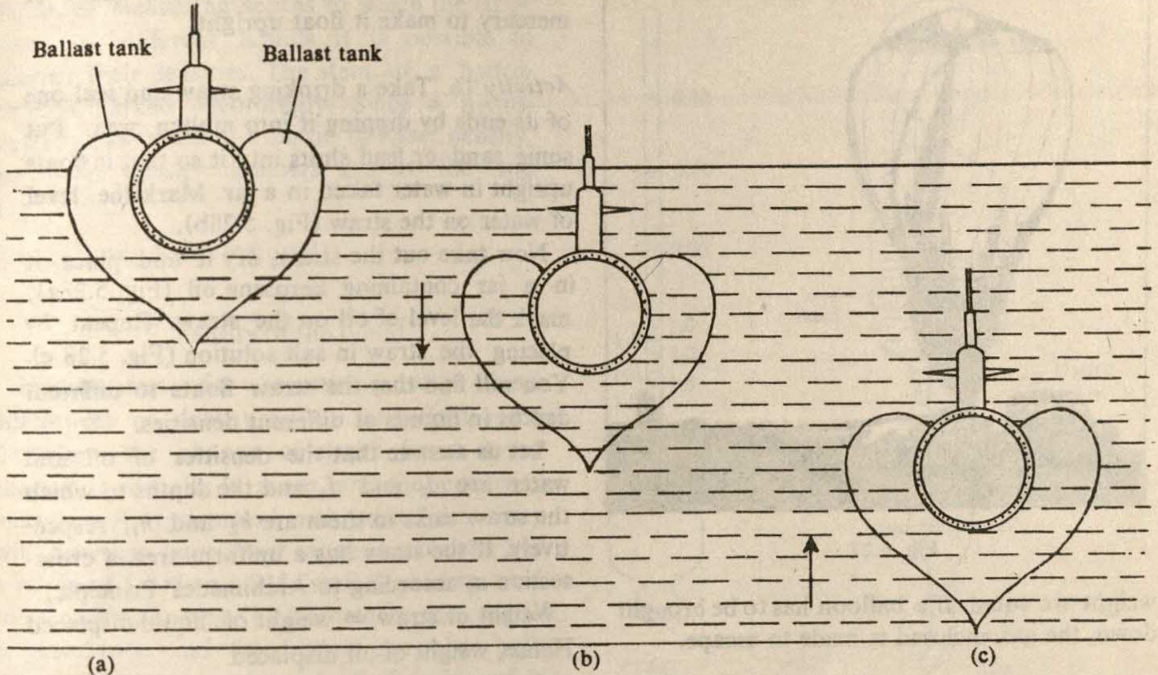


Fig. 5.26

as under the surface as required. It has huge ballast tanks in the hull; when a submarine has to dive, the tanks are filled with water so that the weight increases (Fig. 5.26). To return to the surface again, water is forced out of the tanks.

The density of sea water varies at large depth due to the enormous pressures. Most *fishes* remain at a particular depth in the sea. Many of them have an air sac which can be adjusted to make the upthrust at that depth equal to the weight.

5.15 Balloons and Air Ships

As mentioned earlier, loss of weight is experienced by all objects not only when immersed in a liquid but also in air. The density of air being very small, the upthrust, which equals the weight of air displaced, is very small. However, if a balloon is filled with a gas even less dense than air, such as hydrogen or helium, the upthrust could be greater than the weight of the balloon. In such a condition the balloon will rise above the ground. Toy balloons which rise are filled with hydrogen.

Consider the example of a toy ballon filled with hydrogen of density 0.09 kg/m^3, and of volume 1 litre (10^{-3}m^3). The density of air outside is 1.25 kg/m^3.

Then, weight of hydrogen filled in the balloon

$$= 10^{-3} \times 0.09 \text{ kgf} = 0.09 \text{ gf}$$

Weight of air displaced

$$= 10^{-3} \times 1.25 \text{ kgf} = 1.25 \text{ gf}$$

Hence, resultant force acting upwards

$$= 1.25 - 0.09 \text{ gf} = 1.16 \text{ gf}$$

If the fabric of the balloon and the thread weigh 1 gf, the net upward force which will raise the balloon will be 0.16 gf.

Fig. 5.27 shows a huge plastic balloon being sent up by physicists of Tata Institute of Fundamental Research, Bombay to study the upper atmoshere. It can carry a load of upto 250 kgf to an altitude of 36 km. Since air in the upper atmosphere becomes rarer, upthrust gradually decreases as a balloon rises; the pressure of air outside the balloon also becomes less which increases volume of the balloon and displaces more air. At a particular altitude the equilibrium is reached when upthrust and

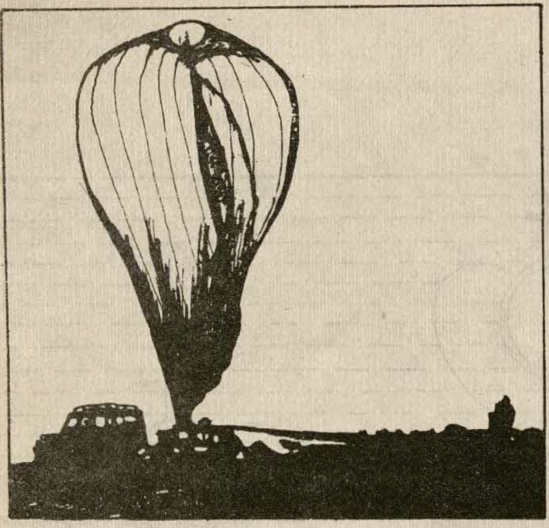


Fig. 5.27

weight are equal. If a balloon has to be brought down, the gas enclosed is made to escape.

5.16 Hydrometer

A hydrometer is an instrument used to find the relative density of liquids. It consists of a narrow glass stem closed at the top which opens into a wider cylindrical bulb. The small bulb at the bottom is loaded with lead shots or mercury to make it float upright.

Activity 16. Take a drinking straw and seal one of its ends by dipping it into molten wax. Put some sand or lead shots into it so that it floats upright in water taken in a jar. Mark the level of water on the straw (Fig. 5.28b).

Now take out the straw, dry it and place it in a jar containing kerosene oil (Fig. 5.28a); mark the level of oil on the straw. Repeat by placing the straw in salt solution (Fig. 5.28 c). You will find that the straw floats to different depths in liquids of different densities.

Let us assume that the densities of oil and water are d_2 and d_1 and the depths to which the straw sinks in them are h_2 and h_1, respectively. If the straw has a uniform area of cross-section a, according to Archimedes' Principle,

Weight of straw = weight of liquid displaced

Hence, weight of oil displaced

= weight of water displaced

$$\text{or} \quad h_2 \times a \times d_2 \times g = h_1 \times a \times d_1 \times g$$

$$\text{or R.D. of kerosene oil} = \frac{d_2}{d_1} = \frac{h_1}{h_2}$$

$$= \frac{\text{depth of straw immersed in water}}{\text{depth of straw immersed in oil}}$$

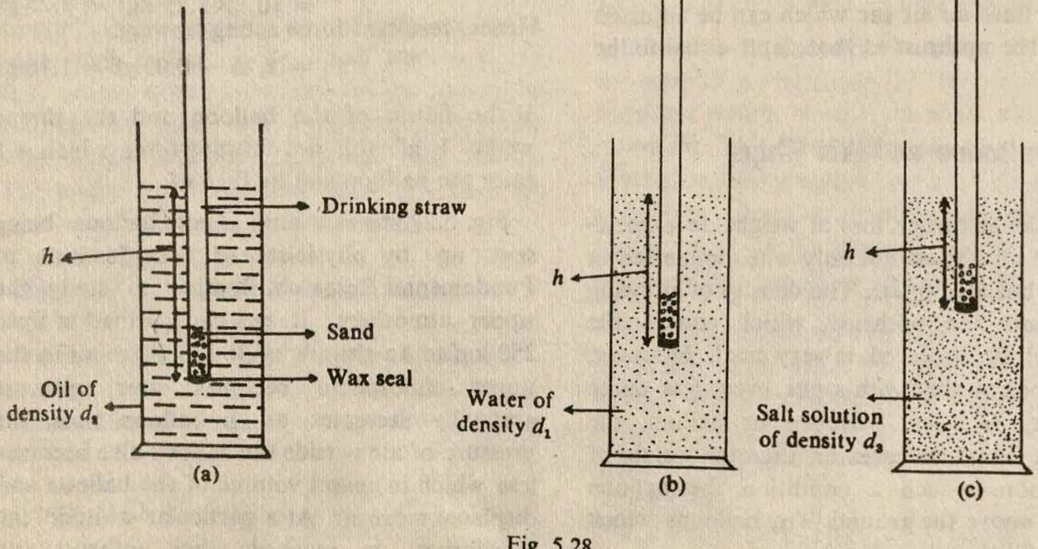


Fig. 5.28

Hence, by measuring depths to which the straw floats in different liquids it is possible to measure their densities. The stem of a hydrometer is marked accordingly. Since a hydrometer sinks more in a liquid of lesser density, the lower density numbers are at the top (Fig. 5.29a).

From above, depth in liquid

$$\propto \frac{1}{\text{density of the liquid}}$$

Hydrometers for measuring very small differences of density have a large float and a thin stem; the change of depth for a given change in density is more and the sensitivity increases. An instrument with greater sensitivity will, however, have lesser range. *Lactometer* has a range of 1.015 to 1.045 for R.D. and is used to test milk. Another hydrometer is enclosed in a glass tube and fitted with a rubber bulb (Fig. 5.29b); it is used to check charging of a car battery by measuring the density of the acid in the battery.

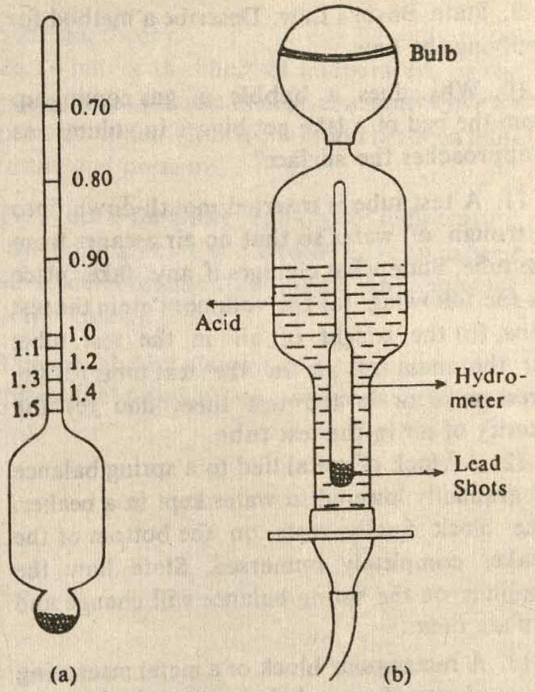


Fig. 5.29

QUESTIONS

1. Explain why a footballer uses studs on his boots.

Is the water tap pressure in a building higher at the top floor or at the ground floor? Explain.

2. Why do fish that normally live at great depths in the ocean burst when brought to the surface?

How can you show experimentally that the pressure of a liquid column increases with increase of depth and increase of the density of the liquid?

3. The base of a rectangular vessel measures 10 cm × 8 cm. A liquid of density 0.8 g/cm^3 is poured into it to a height of 20 cm. What is (a) the pressure exerted on the base; (b) the average pressure exerted on the sides of the vessel, due to the liquid?

4. Calculate the difference of pressure exerted by a column of mercury 75 cm high and a column of water 10 metre high. Given that R.D. of water is 1, while R.D. of mercury is 13.6.

5. Why do trucks and heavy vehicles have four or more rear wheels? A car has its tyres at a pressure of 1.5 kgf/cm^2. What differences, if any, will there be on the tyre pressure, and on the area of tyres in contact with ground, when the car is heavily loaded? Explain.

6. With the help of a diagram explain how you will find out the R.D. of alcohol using a U-tube.

7. What precautions would you take in setting up a simple barometer? What difference, if any, would there be if you take a tube of greater diameter?

8. Why is water not suitable for use in barometers? Which properties of mercury make it more suitable for use in barometers?

9. State Boyle's Law. Describe a method for verifying the Law.

10. Why does a bubble of gas coming up from the bed of a lake get bigger in volume as it approaches the surface?

11. A test tube is inserted mouth-down into a trough of water so that no air escapes from the tube. State what changes if any take place in the following: (a) the volume of air in the test tube; (b) the weight of air in the test tube; (c) the mass of air in the test tube; (d) the pressure of air in the test tube; and (e) the density of air in the test tube.

12. A block of metal tied to a spring balance is gradually lowered in water kept in a beaker. The block finally rests on the bottom of the beaker completely immersed. State how the readings on the spring balance will change and explain them.

13. A rectangular block of a metal measuring 6 cm × 5 cm × 4 cm is held in a liquid of density 0.75 g/cm^3 with its longest edge vertical. Its top surface is 4 cm below the surface of the liquids. Calculate:

(a) pressure of the liquid acting on the top surface of the block;

(b) pressure of the liquid acting on the bottom surface of the block;

(c) force acting on the top surface of the block due to the liquid and its direction;

(d) force due to the liquid, its magnitude and direction, acting on the bottom surface of the block;

(e) resultant (unbalanced) force acting on the block.

14. State Archimedes' Principle. How can you use this principle to experimentally find the R.D. of a piece of wood?

15. How will you find out experimentally the R.D. of a coin employing Archimedes' Principle? Derive the formula used.

16. A glass stopper weighs 100 gf in air, 60 gf in water and 50 gf in brine when completely immersed. Density of water is 1.0 g/cm^3. Calculate (a) volume of the glass stopper; (b) density of glass and (c) density of brine.

17. Five similar glass rods each of length 8 cm are fastened together. They weigh 100 gf in air and 60 gf when completely immersed in water of density 1 g/cm^3. Calculate density of glass and area of cross-section of each rod.

18. What is the Law of Floatation? How does it follow from the Principle of Archimedes'?

19. What part of an iceberg of density 0.9 g/cm^3 is below the surface of sea water of density 1.1 g/cm^3?

20. Apply Archimedes' Principle to explain (a) the equilibrium of an object floating freely on the surface of a liquid; (b) the working of a submarine.

21. Why is a balloon not completely filled up before ascent? Why does an iron nail sink in water while a ship built of iron plates floats?

22. A balloon of volume 300 m^3 is filled with hot air. The mass of the fabric of the balloon and its attachments is 105 kg. If density of hot air is 0.65 kg/m^3 and that of atmospheric air is 1.3 kg/m^3. Calculate the maximum load the balloon can lift.

23. Draw a labelled diagram of a common hydrometer with a range of 0.8 to 1.2. What will happen if the hydrometer is loaded more without changing its dimensions?

24. Explain why (a) a ship sinks deeper when it sails from the sea into a river; (b) the stem of a hydrometer is narrow and it has a heavy **bulb.**

25. In an experiment to investigate the effect of temperature on the volume of a gas at fixed pressure the following readings were obtained:

Temperature (°C)	0	20	40	60	80	100
Volume (cm^3)	11.0	11.8	12.6	13.5	14.2	15.0

Plot a volume-temperature graph taking the temperature axis from − 300°C to +100°C.

Read the temperature when the volume of the gas would reduce to zero. Why will actual observations not follow the line if the gas temperature were to be reduced considerably?

State the law which governs this behaviour of a gas between 0°C and 100°C?

What is the fractional increase in volume per 1°C rise in temperature of the gas between this range of temperature?

26. A gas at 17°C occupies 250 cm^3 of volume at 75 cm of mercury pressure. If the volume is reduced to 200 cm^3 and the pressure remains unchanged, what will be the temperature?

27. What is meant by absolute zero temperature? Explain the meaning on the basis of the kinetic theory.

28. What is the effect of temperature on the pressure when volume is kept constant? Give an expression which gives the relation between temperature and pressure.

29. What is the effect of change of temperature on the boiling point of a liquid? Give an experiment to demonstrate this. Name an appliance which is based upon it.

Draw a labelled diagram of a pressure cooker. Explain the principle on which its working is based.

6

Structure of Matter

You are familiar with the fact that matter exists in the form of solid, liquid and gas; these are called the *three states of matter*. At the normal temperatures around us various materials exist in these different states. A very common example of a material known to exist in the three states is water; it is normally a liquid but also exists as ice (a solid) and water vapour (a gas). What happens when a solid changes into a liquid? A solid has a fixed shape but a liquid or gas does not. Why?

Man has always been deeply interested in matter and its forms. The early Indian thinker *Katyayana* and the Greek philosopher *Democritus* had argued that even though matter appears as a single piece, it is made up of a large number of very tiny particles. This was an ingeneous theory because although there is much evidence now in favour of this argument, no one has actually cut matter into its individual particles. Much of our knowledge about matter is based upon indirect evidence obtained from a large number of observations.

6.1 Particulate Nature of Matter

Activity 1. Take a scent sprayer, a flit gun or a simple apparatus shown in Fig. 6.1 consisting of two tubes and a flask containing some water. Blow hard over the top of the tube *b* through the tube *a*, by pressing the rubber ball. You will observe that the water comes out in a cloud of tiny droplets.

Take one of the tiny drops and view it under a powerful microscope. It looks much bigger. Can the droplet be further broken down?

Activity 2. Dissolve one gram of fluorescein or potassium permanganate in a small volume of water and make up the solution to a litre ($1000\ cm^3$). Note the colour of the solution. Take the solution in a burette and run $10\ cm^3$ of it drop by drop in a test tube; let us assume that it contains 200 drops.

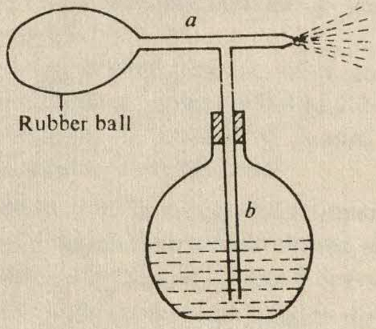


Fig. 6.1

Since each drop looks coloured, it should contain some potassium permanganate. How much?

$1000\ cm^3$ of water contains 1 g of potassium permanganate

$10\ cm^3$ of water contains $\frac{10\times1}{1000}$ g of potassium permanganate

or 200 drops of water contains 0.01 g of potassium permanganate

Hence, 1 drop of water contains $\frac{0.01\ \text{g}}{200}$

$= 5\times10^{-5}$ g of potassium permanganate

Now dilute 10 cm^3 of this solution in the test tube to 1 litre. You will find that although the colour has become faint, you can still detect it. The second solution is diluted in the ratio of 10 : 1000; hence each drop of the second solution contains $\frac{5\times10^{-5}\ \text{g}}{100} = 5\times10^{-7}$ g of potassium permanganate. In other words, 1 g of potassium permanganate has been sub-divided in 2 million particles. Perhaps there are more than two million particles in 1 g of potassium permanganate! These experiments indicate that matter consists of a very large number of tiny particles. They must be extremely small. How small!?

6.2 Size of a Molecule

It is a common experience that a small drop of oil spreads considerably on the surface of water. This phenomenon gives a possible method of finding out the size of oil molecules.

Activity 3. Take a clean tray and coat its inner side with wax to ensure that there is no oil or grease inside it. Fill the tray to a depth of about 2 cm with water and level it. Now sprinkle some *lycopodium* powder over the clean surface of water.

Take a fine iron wire and dip it in olive oil; you will see that a number of small droplets stick on the wire. With the help of another wire make a big drop which has a diameter of 0.5 mm as seen against a metal scale (Ordinary scales will not have 0.5 mm marks). If we assume this drop to be cubical in shape then, approximately, its volume

$$= (0.05\ \text{cm})^3 = 1.25\times10^{-4}\ \text{cm}^3.$$

Now dip the wire in the water; the drop will spread out into a circular film (Fig. 6.2).

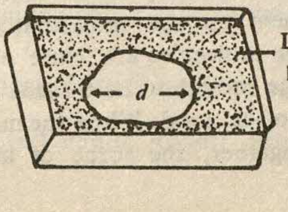


Fig. 6.2

Measure the diameter of the film d. If we assume that the film surface is a square of side d cm, its area is d^2 cm^2. If the film is considered to be h cm thick, the volume of the oil film $= d^2\times h$ cm^3. Let $d = 25$ cm in the experiment. Then, volume of the film $= 25^2\, h = 625\, h$ cm^3

Hence $\qquad 625h^2 = 1.25\times10^{-4}$

From it we obtain, thickness of the film

$$h = \frac{1.25\times10^{-4}\ \text{cm}^3}{625\ \text{cm}^2} = 2\times10^{-7}\ \text{cm}$$

Even if we assume that the film consists of a single layer of oil particles, we find that the thickness of one oil particle is of the order of 10^{-7} cm or 10^{-9} m. Other oils may spread even more. If a film of olive oil is 10 or 10^2 particles thick, the size of a particle must be even smaller. We shall call the smallest particle of a material a *molecule*.

6.3 Intermolecular Spacing

We have seen that it is easy to make our way through air; one can even make one's way through a liquid, but we cannot go through a solid. How are the molecules of a solid, a liquid and a gas packed?

Activity 4. Fill a beaker with glass beads or marbles. Now pour fine sand in it. You will observe that a lot of sand will settle in the beaker without any overflow. This shows that there is a lot of space in the beaker even when it is filled with marbles.

Pour 20 cm^3 of finely powdered sugar in a jar. Now add to it a measured quantity (200 cm^3, say) of water; stir the solution till the sugar is completely dissolved. You will notice that the volume of the solution is not 220 cm^3 but very close to 200 cm^3.

The experiment suggests that the sugar molecules on dissolving in water occupy empty spaces between molecules of water. *Molecules of all matter are separated from each other by spaces which are actually larger than the size of molecules themselves.*

Activity 5. Fix a rubber cap tightly over the mouth of a syringe whose piston has already been pushed fully into the cylinder. With another small syringe fitted with a needle, introduce 1 cm^3 of water into the bigger syringe (Fig. 6.3). Dip the bigger syringe in a large beaker containing boiling water. As the water in the syringe changes into steam, you will notice that the piston is pushed outward.

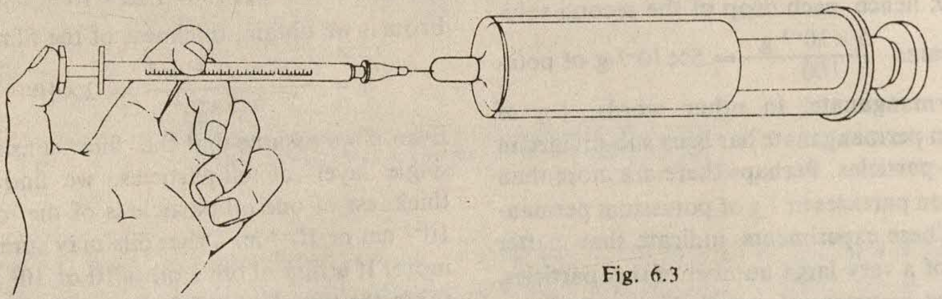


Fig. 6.3

Thus, the volume is greatly increased as water changes into steam. The experiment suggests that the spacing between molecules of steam is much greater than that between molecules of water. When a liquid changes into the gaseous state, the average spacing between molecules increases.

Activity 6. Heat some wax in a hard glass test tube till it melts completely. Allow the wax to cool. On changing back into solid, you will observe that the surface of the wax is concave. This shows that on changing from liquid to solid state, the volume of wax has become less. This leads to the conclusion that the molecular spacing has been reduced.

Molecules in a liquid are generally less closely packed than those in a solid of the same material. Gas molecules of the same material are even more loosely packed.

6.4 Intermolecular Forces

Molecules, as we have studied, are very tiny in size and their number in any object is very large. Their intermolecular spacing is also very small. How are they held together?

On lifting a scale or a pencil, the whole of it is lifted as one piece. This is only possible when their molecules pull each other.

Stretch a rubber band gradually with an increasing force. To keep it stretched you have to keep applying the stretching force on it. On releasing the applied force, the rubber band restores to its original shape.

Thus, on applying a force greater than the intermolecular force, the molecules are relatively displaced; a stretching force will move them further away from one another. On releasing the external force, the intermolecular force restores the band to its original condition.

The force of attraction between the molecules of the same substance is called the **force of cohesion**. The force is maximum in solids and least in gases.

Activity 7. Put a drop of water on a glass slide and place another slide on it. Try to separate the two slides from each other. You will observe that a force is definitely needed. Take water in a beaker and pour it out. You will find some drops of water still sticking to the glass. This shows the presence of a force between glass and water. *This force of attraction between molecules of dissimilar materials is called the* **force of adhesion**. It is the force of adhesion between molecules of paper and paste that sticks two pieces of paper together. If there exists a force of attraction between molecules, why do two blocks of glass or wood when brought together do not stick?

The answer to this question is the distance between them on the molecular scale is very great. When molecules are 'close' enough, the force is large enough to hold them together in the form of a solid. When the molecules are not close together, the force of attraction is negligibly small. The distance upto which molecular attraction is adequate is called the *molecular range*. It is larger than the size of molecules, but not much more.

Experience shows that it is not easy to compress solids. Steel beams used to support buildings or bridges are compressed a bit, but they regain their original condition when the force is removed. This shows that when molecules are pushed together, there exists a force of *repulsion* as well. Greater the applied force, less is the distance between molecules and more is the repelling force; when the applied force is withdrawn, the force of repulsion brings the material to its original shape.

The normal distance of separation between molecules is of the order of 10^{-8} cm. If the distance between the molecules is increased by the application of an external force, a molecular force of attraction comes into existence. Hence, a stretched spring, rubber band or a wire regain the original length when the external force is withdrawn. When the distance between molecules is made less than 10^{-8} cm, they then repel each other.

6.5 Molecular Motion

In order to have a clearer picture of the particulate nature of matter, and to understand many of the physical phenomena, it is necessary to consider molecular motion.

Activity 8. Open a bottle of ammonia or a perfume in a classroom. Students in the class are asked to raise their hands when they detect the smell. It will be noticed that a student further away from the smelling substance raises his hand later than another student who is closer.

You may have noticed that naphthalene balls (moth balls) packed with wooden clothes gradually become smaller and disappear. This is because molecules of the substance keep escaping from the balls to the surrounding air.

6.6 Brownian Movement

In 1827 British botanist Robert Brown, while observing pollen grains floating in water, noticed that they were in a continuous states of irregular or haphazard movement.

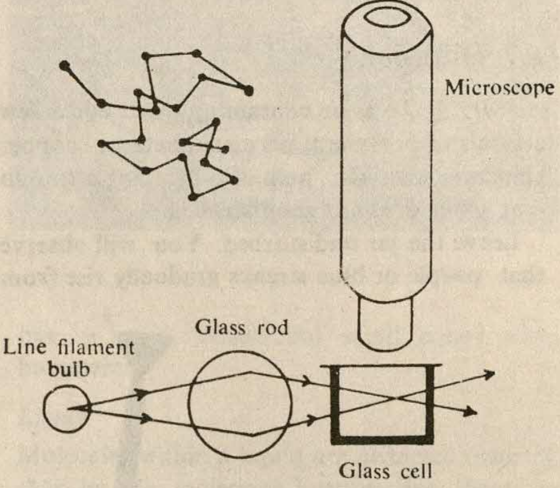


Fig. 6.4

Take a small glass cell containing tiny graphite particles suspended in water, or smoke which contains carbon particles suspended in air. The particles are strongly illuminated by light focussed from a line filament lamp by a glass rod which acts as a convex lens of small focal length. These particles scatter the light incident on them and they appear like starlets when viewed under a microscope. They are found to execute random motion as that of Brown's pollen grains. It is essential that the particles must be very fine if their movement is to be seen. They are large enough to be seen microscopically and are sufficiently small to be affected by the impacts of air or water molecules on them.

Brown could offer no explanation for this movement, but many years later it was realised that the Brownian movement of smoke particles or pollen grains is caused by the bombardment of gas or water molecules on them. The water or air molecules are too small to be observed even by the best known optical microscope; however the haphazard movement of comparatively much larger particles of pollen grains caused by the bombardment of molecules on them provides us evidence of *Brownian movement* of individual gas or liquid molecules. Brownian movement is one of the most striking examples of evidence in favour of the existence of molecules and their motion.

6.7 Diffusion

Activity 9. To a jar containing water add a few crystals of poatssium permanganate or copper sulphate with the help of a drinking straw so that water does not get distrubed.

Leave the jar undisturbed. You will observe that purple or blue streaks gradually rise from the crystals and are spread out in all directions (Fig. 6.5). The water slowly gets coloured showing thereby that molecules of water carrying particles of potassium permanganate move about in all directions in the jar.

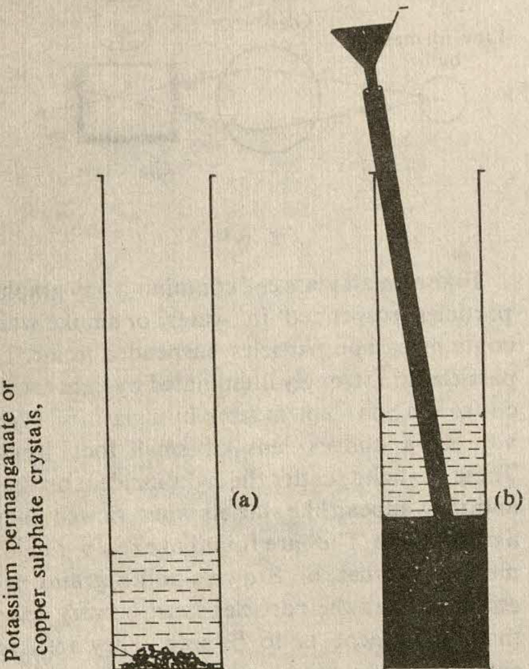


Fig. 6.5

Activity 10. Pour water in a tall jar and then pour denser copper sulphate solution down a funnel to which a long tube has been attached (see Fig. 6.5b). By doing so the second liquid is added to the first without much disturbance.

Leave the jar undisturbed. You will notice that gradually the blue coloured layer of separation rises above and after a few hours the whole of the liquid in the jar gets coloured.

Activity 11. Take a glass tube about 50 cm long and 2 cm in diameter, open at both the ends. Two cotton plugs are placed at the two ends. One is soaked with concentrated hydrochloric acid (HCl) and the other with a concentrated solution of ammonium hydroxide (NH_4OH) (Fig. 6.6).

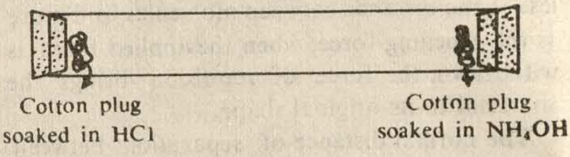


Fig. 6.6

Within a few minutes you will observe a white ring of the fumes of ammonium chloride formed in the tube, closer to the plug of hydrochloric acid. This experiment shows that molecules of hydrochloric acid and ammonia diffuse to the other end of the tube and, where they meet, they form molecules of ammonium chloride. The experiment further shows that the lighter molecules of ammonia (molecular weight 17) diffuse quicker than the molecules of hydrochloric acid (molecular weight 36.5).

When molecules of one substance mix with the molecules of other substance due to their gradual haphazard movement, the phenomenon is called **diffusion.** Heavier molecules diffuse slower than the lighter molecules.

6.8 The Kinetic Theory of Matter

On the basis of the above experiments, the main points of the Kinetic Theory of Matter can be written as follows;

1. All matter is made up of tiny particles called molecules. Molecules of any substance are too small to be seen under an optical microscope (can be seen with an electron or ion microscope).

2. The molecules are separated from each other by a distance called intermolecular

distance (in a gas this is named as the mean free path which is the mean distance between any two collisions of molecules). The intermolecular space is greater than the size of a molecule. It is least in solids and is the maximum in gases.

3. The molecules attract each other with a force called intermolecular force of attraction. It is the maximum in solids and is the minimum in gases.
4. The molecules of matter are in a constant state of motion and hence possess kinetic energy. The molecules of a solid vibrate about their mean position; molecules in a liquid are free to move about within the liquid and the molecules of a gas are free to move about anywhere.
5. Temperature of a substance is the measure of the mean kinetic energy of its molecules.
6. The molecules of a gas collide with each other and the walls of the container. These collisions are assumed to be elastic which means that there is no loss of energy at the collision.

6.9 The Three States of Matter

Matter commonly exists in either solid, liquid or gaseous state.

Solid

The molecules of a solid substance vibrate about their zero resultant force positions, alternately attracting and repelling other molecules. The intermolecular forces are the maximum. This is why solids have definite size and shape.

All true solids are crystalline in nature. This is because in solids molecules are arranged in regular patterns called the *lattice.* Even the metals and the snow which falls on high altitudes are crystalline. Fig. 6.7 gives the magnified view of various types of snow crystals.

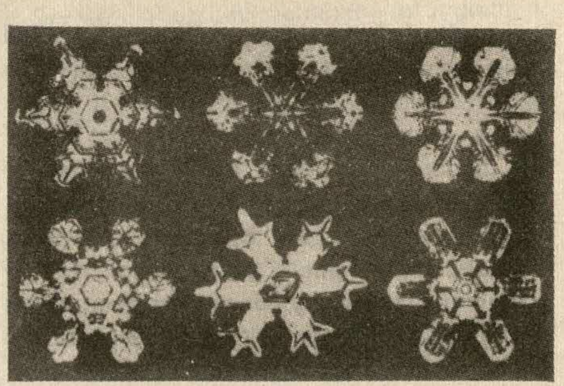


Fig. 6.7

There is however a borderline case of materials which appear to be solids but actually are viscous liquids. For example, pitch, like a liquid, slowly flows out when placed in funnels and, like a solid, breaks into small pieces when hammered.

Liquid

Molecules within a liquid are attracted from all sides by the molecules surrounding them, so that the total force acting on them averages zero. On the other hand, molecules on the surface are only pulled inwards by the molecules lying underneath them. This inward force tends to reduce the free surface, and thereby the surface area, of the liquid. For a given volume the surface area is the minimum in a sphere. This is why drops of liquids acquire spherical shape.

Liquid molecules can move freely within the liquid. This freedom of movement enables a liquid to take the shape of the vessel in which it is contained.

Liquids however have a surface from which molecules are usually unable to escape due to the attraction of molecules lying below them. Because of this liquids have a **definite size.**

Some energetic molecules are likely to escape from the surface and become free as the molecules of a gas. This process is called evaporation.

Gas

The molecules in a gas are much further apart than those in solids and liquids. The intermolecular force between them is therefore negligible and they move about at random in all directions colliding with one another and with the walls of the container. The average distance moved by a molecule between two collisions is called its *mean free path*. At atmospheric pressure, the mean free path of air is only about 10^{-6} mm, while at great altitude where the pressure is very low, the mean free path is several kilometres.

Because of the negligible force of attraction (unless the gas is highly compressed) between the molecules of a gas, a gas is perfectly free to expand and completely fills the vessel in which it is contained. This is why gases have no definite size or shape of their own.

The kinetic theory provides explanation to a number of other phenomena such as gas laws, boiling, melting, evaporation, etc.

6.10 Melting

The change of state from a solid to a liquid is called **melting** and the temperature at which it takes place is called **melting point.**

In a solid, molecules are arranged in a definite pattern, and they vibrate about their mean fixed positions of zero resultant force. When the temperature is raised, their speed of vibration and hence their kinetic energy increases and the force of attraction between them decreases. A stage is reached when the force of attraction becomes so small that the molecules begin to slip and slide over each other and assume the shape of the container that is, the solid changes to a liquid. The temperature at which this occurs is called melting point and such a process is called melting.

During melting, energy is required in separating the molecules against the forces that bind them into fixed positions. This is supplied by the heat provided, and increases the potential energy of the molecules. This is why during melting the kinetic energy of molecules or the temperature of the gas remains constant.

6.11 Evaporation

At any temperature the average kinetic energy of all the molecules is the same though some molecules may be moving faster than others. The more energetic molecules may possess enough energy to escape from the surface into the air above. This process is called *evaporation*.

During evaporation molecules possessing more energy escape leaving behind the slower ones. The mean kinetic energy of the molecules left behind becomes less and hence the temperature of the liquid decreases. Evaporation, therefore, causes *cooling* of the liquid.

6.12 Boiling

When a liquid is heated it is observed that at first its temperature rises, then it becomes constant and the liquid rapidly changes into its vapours at this constant temperature. Bubbles of vapour are seen to emerge and rise to the surface of the liquid. This phenomenon is called **boiling** and the constant temperature at which it occurs in a liquid is called the **boiling point** of the liquid.

On heating a liquid, the energy supplied makes the molecules of the liquid move faster and faster and the mean kinetic energy of the molecules increases. Therefore, the temperature, which is a measure of the mean kinetic energy of molecules, rises.

As the temperature rises, molecules move faster and faster and thereby the intermolecular forces of attraction decrease. A stage reaches when this force of cohesion becomes so small, that any further energy supplied is enough to free the molecules from the force of attraction of the neighbouring molecules. The molecules then escape from the liquid in the form of vapour. This process is called **boiling.** During boiling the mean kinetic energy of the molecules of the liquid remains the same and thus the temperature of the liquid remains constant. However the potential energy of the molecules increases.

6.13 Pressure and Kinetic Theory of Gases

Air pumped into a balloon exerts pressure on the walls of the balloon in all directions, i.e. upwards as well as downwards and sideways.

Air is composed of a large number of molecules which move haphazardly in all directions. They hit the sides of the container with a certain momentum (equal to *mv*) and bounce back with a negative momentum (equal to $-mv$). Hence the change in the momentum is $mv-(mv)=2mv$. The rate of change of momentum is proportional to the force exerted on the walls and the force per unit area is the pressure. We may therefore say that the molecules of air bombard the walls of the container and bounce back, hence exerting pressure on the walls of the container. As the number of molecules bombarding unit area of the walls is very large, the average pressure exerted on all sides of the container is the same.

On raising the temperature of air, the molecules move faster and faster. As a result the change of momentum on each impact becomes more and the number of impacts on a given area per unit time also increase. Hence the pressure increases. This is the **pressure law**.

Keeping the temperature same, if the volume is decreased, the distance travelled by a molecule before it collides against the same wall decreases. Therefore the number of impacts per second become more and pressure increases. Hence with decrease in volume the pressure increases. This is **Boyle's law**.

6.14 Absolute Zero

If two objects are at the same temperature, their molecules have the same average kinetic energy. As an object is cooled, the mean kinetic energy of molecules decreases and they slow down, thus occupying less space. If you could cool down an object until all its molecules come to rest, you would have it at its coldest possible temperature. Scientists call this temperature **absolute zero**. They formerly believed that at this temperature all molecular motion stopped, but now they know that this is not true. Rather, *absolute zero is the temperature at which the molecules have the lowest possible energy*. They are very nearly at rest. Absolute zero is $-273°C$ or $-460°F$. The absolute zero temperature is, however, impossible to acheive.

QUESTIONS

1. Discuss briefly two evidences in each case which show that

(a) All matter is made up of a very large number of very tiny particles;

(b) There are empty spaces between molecules in a matter;

(c) Forces of attraction and repulsion are acting between molecules in a matter;

(d) Molecules of matter are in constant motion.

2. Describe a simple experimental method of estimating the size of a molecule of matter. Give necessary calculations.

3. One gram of potassium permanganate contains approximately 2×10^{21} molecules. It is dissolved in one litre of water. One cm^3 of this water is now taken in another beaker and water is added to it to make one litre. Calculate:

(i) Mass of potassium permanganate present in 1 cm^3 of the second solution.

(ii) Number of potassium permanganate molecules present in 1 cm^3 of the second solution.

4. One drop of a solution of stearic acid placed on a large surface of water spreads out into a circular film of area about 50 cm^2. The drop has a volume of approximately 10^{-5} cm^3. Find the size of a molecule of a stearic acid. What assumption has been made?

5. A beaker is completely filled with water. A spoonful of common salt is slowly added to it. The salt dissolves yet the water does not overflow. What can be deduced from this experiment?

6. What is meant by Brownian movement? Sketch the Brownian movement of a particle observed in a gas. Explain the motion observed.

What is the mean free path of the moving particle?

7. What do you understand by Brownian motion? What does it indicate?

8. What is meant by diffusion? Describe one experiment to show in each case the diffusion of (a) one gas into another; (b) one liquid into another.

9. Bromine vapour set free in air slowly diffuses in air, but when liberated in a vacuum fills the available space very quickly. Explain why?

10. It is stated that the molecular theory shows a mixture of perfect order and perfect disorder. Discuss this statement with respect to the kinetic theory of matter.

11. On the basis of the kinetic theory of matter state the difference between:

(a) solid, liquid and a gas;

(b) evaporation and boiling;

(c) melting and freezing.

12. How does kinetic theory of matter explain:

(a) The phenomenon of diffusion;

(b) The fact that diffusion is more rapid in gases than in liquids?

13. On the basis of kinetic theory of gases how can you explain that

(a) gases exert pressure on the walls of the container.

(b) the pressure of a gas increases with

  (i) increase of temperature

  (ii) decrease in volume.

14. What do you mean by absolute zero? Explain on the basis of the kinetic theory of matter that absolute zero is the coldest possible temperature.

7

Temperature and Volume Change

One of the most significant steps of mankind towards material progress has been the control and use of fire for doing useful work. This was achieved thousands of years ago. However, modern civilization really began only a few hundred years ago when man invented steam and petrol engines which enabled him to do a lot of work without employing much physical labour. Fuel is burnt in these engines to produce *heat* which is utilised to do useful *work*. Thus in heat engines *heat is changed into mechanical energy.* It is also common knowledge that on hammering a small piece of metal or drilling a hole in it, heat is produced. On applying brakes to a running car, work is done against friction which changes into heat. The car stops and the wheels become warm. Thus in the above examples *mechanical energy is converted into heat*. We can say that **heat** *is a form of energy which makes the objects feel warmer.*

7.1 Heat and Temperature

Water in a vessel kept over a kitchen stove becomes 'warm' and feels 'hot' once it starts boiling. A piece of metal held in flames becomes very hot. The degree of hotness of a body can be indicated in terms of its *temperature.* Thus **temperature** is the degree of hotness of an object on some chosen scale. The temperature of a body rises on heating. It is common knowledge that heat flows from a body at a higher temperature to the one at a lower temperature till their temperatures are equal. We can, therefore, say that **temperature** *is the physical state of a body which determines the direction of flow of heat when it is placed in contact with another body.*

Heat and temperature are related to each other as *cause and effect*. Whenever we heat a body, if there is no change of state from solid to liquid or from liquid to a gas, its temperature rises.

Activity 1. Take a partially evacuated tube containing some mercury having some small pieces of glass floating over it. On heating the tube gradually from below, it is observed that the glass pieces begin to jump up and down; the jumping becomes vigorous as the temperature rises (see Fig. 7.1).

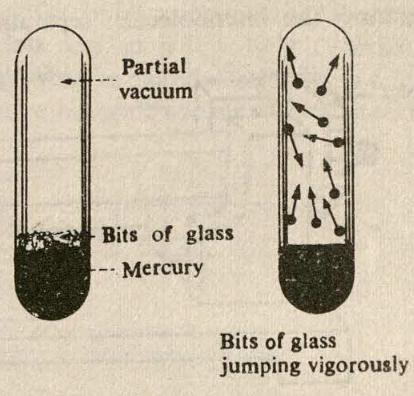


Fig. 7.1

According to the kinetic theory of matter, molecules of mercury are free to move about haphazardly within it. At low temperatures the random motion of mercury molecules is not vigorous enough to produce noticeable effect on the glass pieces when they bombard them. As the temperature is increased, the kinetic energy of mercury molecules increases and when they now bombard the glass pieces the latter begin to dance. This experiment shows that the kinetic energy of the molecules of a substance increases with the increase of temperature.

All the molecules do not possess the same kinetic energy. **Temperature** *of an object is the measure of the mean kinetic energy of its molecules.*

7.2 Temperature and Volume

A number of physical properties change with temperature. Among these the most important is the change in volume. Most of the objects expand with the rise of temperature and contract on cooling. Gases expand the maximum and solids the minimum.

According to the kinetic theory of matter, the temperature of a body is a measure of the mean kinetic energy of its molecules. With the increase of temperature, kinetic energy of molecules increases and they begin to move about more vigorously. The situation can be compared to a dance at its peak; the couples dance about vigorously and the distance between any two couples increases. Similarly with the increase of temperature the intermolecular separation becomes larger and hence the substance expands. On cooling molecules slow down; the molecular separation becomes less and the substance contracts.

7.3 Expansion of Solids

Solids expand on heating, but the expansion is too small to be seen easily. This is why carefully designed experiments are required to show this effect.

Activity 2. Take a ball and ring apparatus as shown in Fig. 7.2. At ordinary temperature the ball can just pass through the ring. When the ball is heated over a flame it is noticed that it can no longer pass through the ring. On cooling it contracts and again passes through.

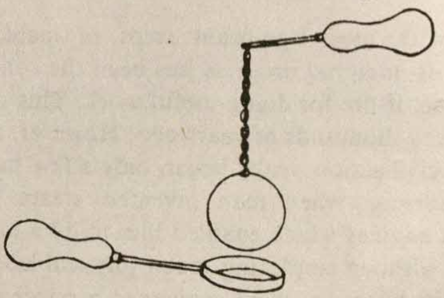


Fig. 7.2

During expansion and contraction of solids tremendous forces come into play. This can be shown by the bar-breaker apparatus as shown in Fig. 7.3.

Activity 3. The bar-breaker apparatus consists of a strong iron frame holding a steel rod. One

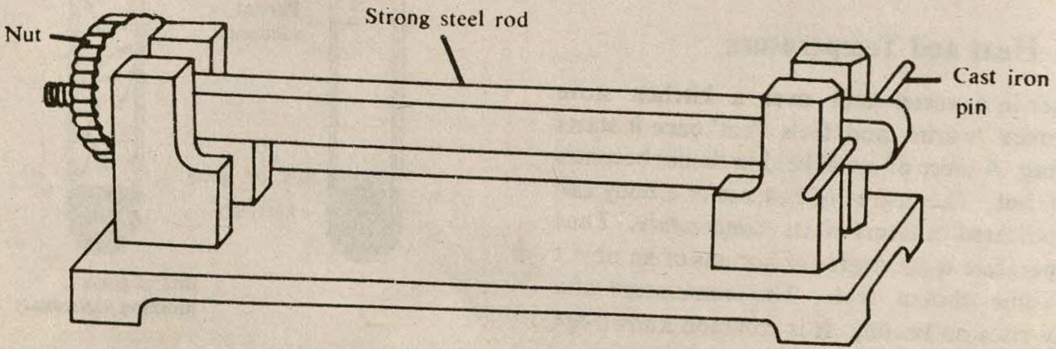


Fig. 7.3

end of the rod is threaded so that it can be screwed up; through a hole near the other end a small cast iron pin is slipped in. The steel rod is heated strongly with a flame from a blow-burner and when it is hot the nut is tightened. On cooling, as the rod contracts the cast iron pin is found to break up into many small pieces, showing thereby that the rod exerts a stroug force on contraction.

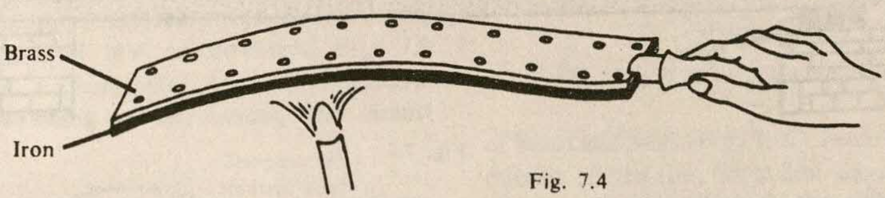


Fig. 7.4

Different metals of the same length when heated through the same rise of temperature have different expansions. The rate of expansion of brass and aluminium is almost twice that of iron. Platinum and glass show equal expansion on heating. This is why a platinum wire can be fused in a glass rod while a copper or brass wire cannot be fused in it.

Activity 4. Take a bimetallic strip having two equal strips of brass and iron riveted together firmly. On heating it is noticed that it bends with brass on the outer side of the bent curve (see Fig. 7.4). This shows that brass expands more than iron, other factors remaining the same.

7.4 Expansion and Contraction in Everyday Life

Expansion of solids poses problems for engineers. Sometimes the expansion is used to our advantage but more often large forces that accompany expansion and contraction of solids are a disadvantage in engineering. A few simple cases are described in the following.

(*i*) *The Railway Track*

The mid-day sun specially in summers, causes the railway lines to become hot. The lines expand and if no space is allowed for their expansion, they may bend and cause derailment. Gaps are, therefore, always left between two sections of a railway line so as to give space for them to expand (Fig. 7.5).

At each gap, the two sections are joined by fish plates clamped to the rails by bolts as shown in Fig. 7.5. In order to allow movements of rails at the joints the holes through which bolts pass are made oval.

(*ii*) *Cracking of Glassware*

You might have noticed that a thick glass tumbler breaks when very hot water or tea is poured into it. The hot liquid causes the inside to expand before the outside. The strain thus set up is too much for the glass and it cracks. Pyrex glass expands less and so is less likely to break. A 'pyrosil' dish can be placed straight into a refrigerator from a hot plate cooker without cracking.

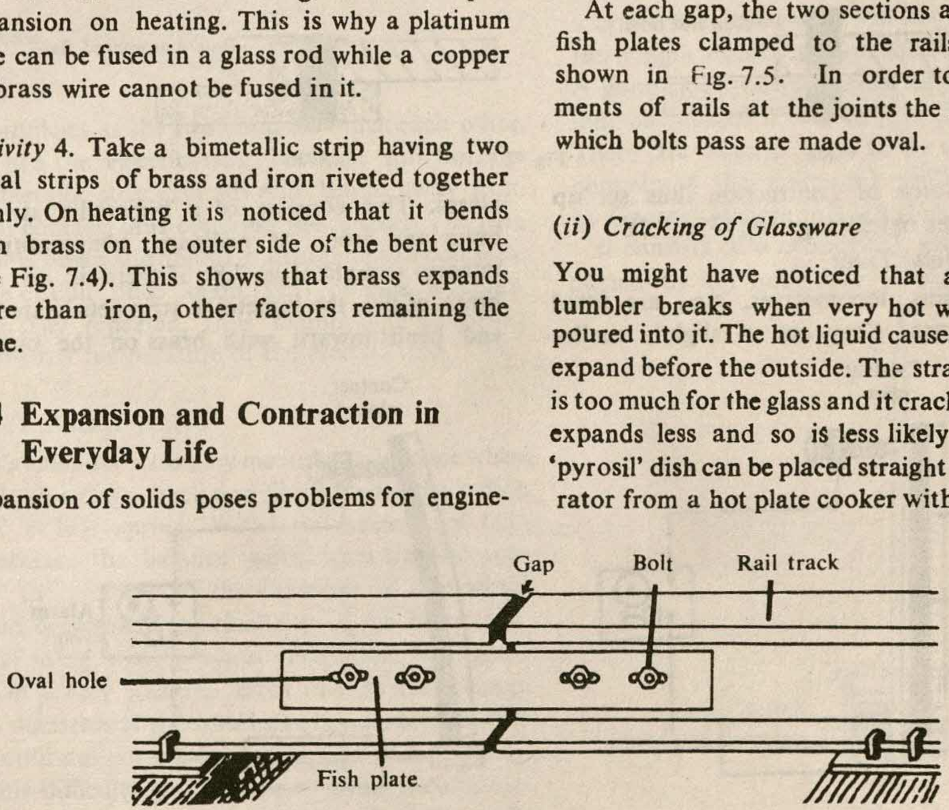


Fig. 7.5

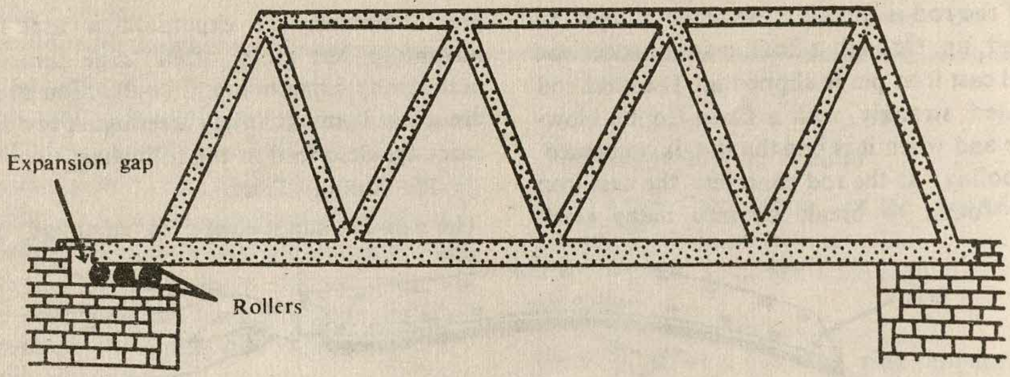
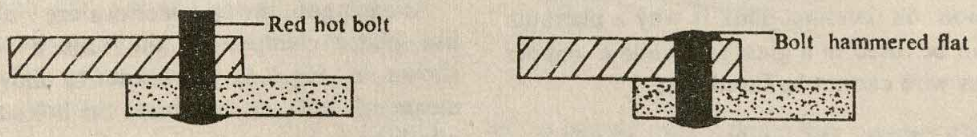


Fig. 7.6

(*iii*) *Riveting*

Two metal plates or beams can be riveted together by utilizing the large force set up during contraction. Holes are drilled in the two plates to be joined and a red hot bolt or rivet is passed through them. It is then hammered flat while still red hot and is cooled by pouring water. The force of contraction thus set up pulls the plates tightly together (Fig. 7.7).



(a) Fig. 7.7 (b)

(*iv*) *Fixing Metal Tyres*

Wheels of trains, locomotives, etc., are fitted with steel tyres. They are of slightly smaller diameter than the wheels. Tyres are heated strongly and the hot expanded tyre is slipped over the rim of the wheel. It is then cooled by pouring cold water over it. The tyre contracts and grips the wheel tightly.

(*v*) *Automatic Fire Alarm*

Many modern buildings have an automatic fire alarm. This consists of a bimetallic strip of brass and iron. At ordinary temperature it remains straight (Fig. 7.8). If there is an outbreak of fire, the bimetallic strip gets heated up and bends inward with brass on the outside

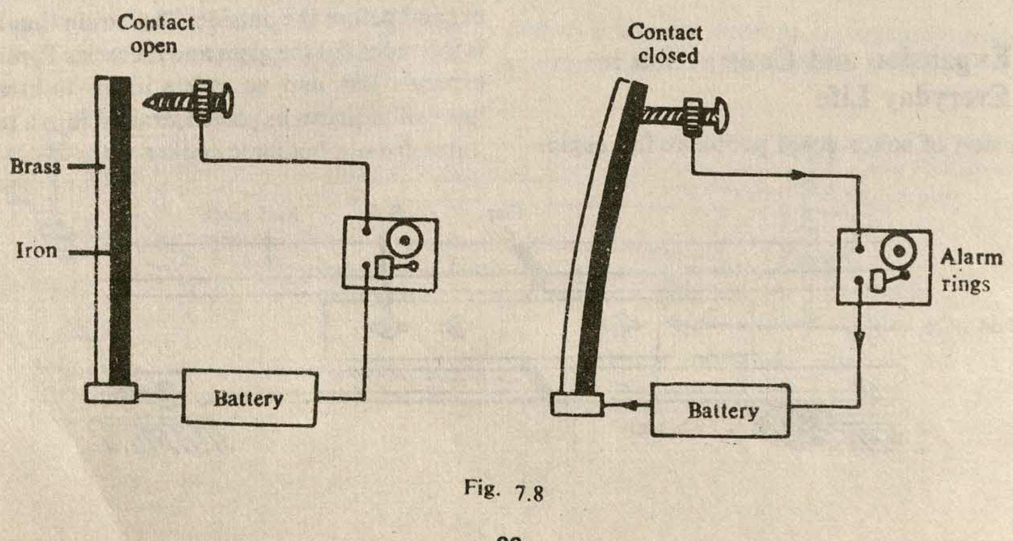


Fig. 7.8

of the curve. This is because brass expands more than iron. Thereby the circuit completes and the alarm starts ringing.

(vi) *Thermostat*

A thermostat is a device which can maintain a steady temperature by automatically breaking and completing a circuit. It uses a bimetallic strip and is used in electric ovens, electric irons, refrigerators and air conditioners. Fig. 7.9 shows how a thermostat works in an electric iron. On switching on the current, the circuit completes as the two contacts touch each other. When the electric iron becomes too hot, the bimetallic strip expands and bends away from the contact, thus breaking the circuit. The iron cools down and the strip straightens to complete the circuit once again. This process is continuously repeated, thus maintaining an almost constant temperature of the electric iron.

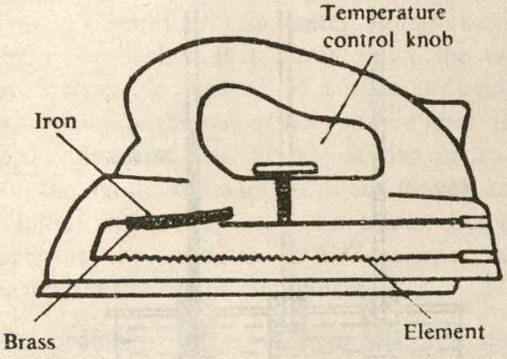


Fig. 7.9

(vii) *Balance Wheel*

Watches keep time by means of a balance wheel which swings back and forth under the action of a hair spring. With the increase of temperature the balance wheel loses time because of the increase of the diameter of the wheel and decrease of the elasticity of the hairspring. By using invar, whose coefficient of expansion is very low, the error due to the change in diameter of the wheel can be avoided but this would not correct the weakening of hairspring. This difficulty is overcome by using a compensated wheel. The rim of the wheel is made of brass and steel (Fig. 7.10), brass being on the outside of the rim. On a hot day, the balance wheel will expand and the hairspring will weaken, but this is compensated by an inward curving of the bimetallic rim.

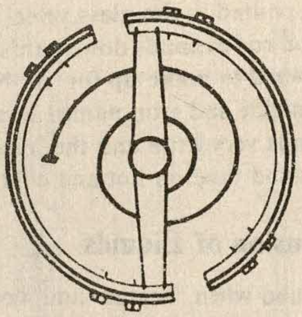


Fig. 7.10 Compensated wheel

(viii) *Compensated Pendulum*

In summer the length of a pendulum increases; a longer pendulum oscillates with a greater time period. It will then make lesser number of vibrations in a day and will lose time. In winter, the length contracts and the clock gains time. A good clock must keep the length of its pendulum unchanged if it is to give the correct time. There are several ways to do so and the most common is the mercurial pendulum invented by George Graham in 1716 (Fig. 7.11).

It consists of a cylindrical glass vessel supported by an iron rod. A right amount of

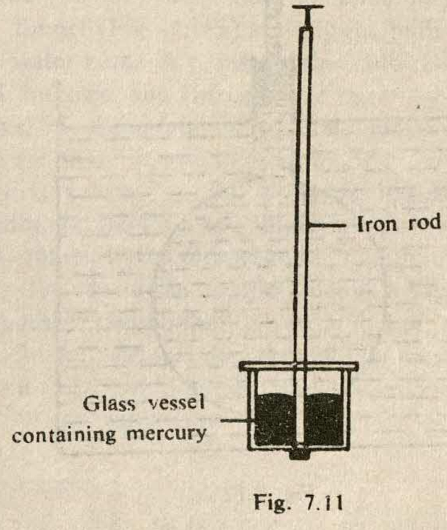


Fig. 7.11

mercury is poured in the glass vessel such that when the iron rod expands downwards, mercury expands upward to make up for it. Nowadays an alloy of nickle and iron named **invar** is used which expands very little and the clocks keep reasonably good time on hot and cold days.

7.5 Expansion of Liquids

Liquids expand when heated and contract on cooling. The expansion and contraction is appreciable and can easily be seen.

Activity 5. Fill a round-bottomed flask completely with coloured water and insert a rubber stopper carrying a narrow tube into its neck such that some of the coloured water rises a short way up the tube. Mark the position a of the coloured water. Now plunge the flask into a can of hot water and record the level of water in the tube. It is noticed that first the level falls down a little to *b*, due to the expansion of the flask and then rises above *a* to *c* due to the expansion of liquid (coloured water). This shows that liquids expand more than solids.

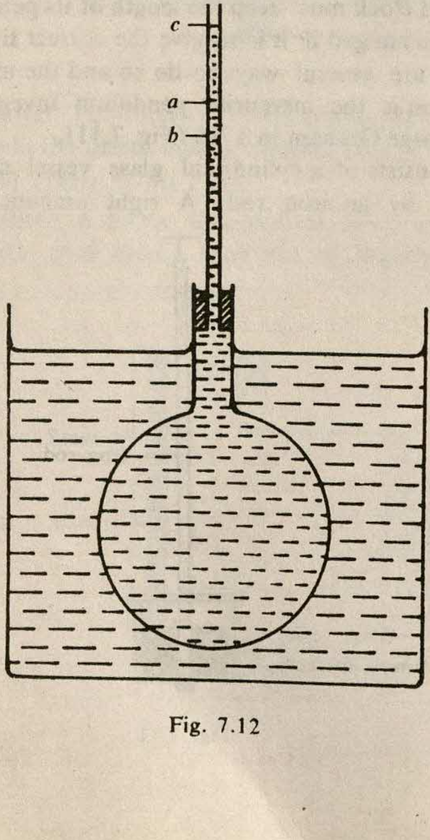


Fig. 7.12

ab = Expansion of flask
ac = Apparent expansion of the liquid
bc = Real expansion of the liquid
As $bc = ac + ab$

Real expansion of liquid = Apparent expansion of liquid + Expansion of the container

Different Liquids Expand Differently

Activity 6. Take three boiling tubes of the same size and fill them with alcohol, water and mercury. Insert rubber stoppers carrying long narrow tubes of the same bore in the boiling tubes such that alcohol, water and mercury stand at the same level. Place the boiling tubes in a large beaker of water and leave them there for some time. Check that all the liquid levels are the same; if neccesary add a little more liquid in the tube in which the level is lower.

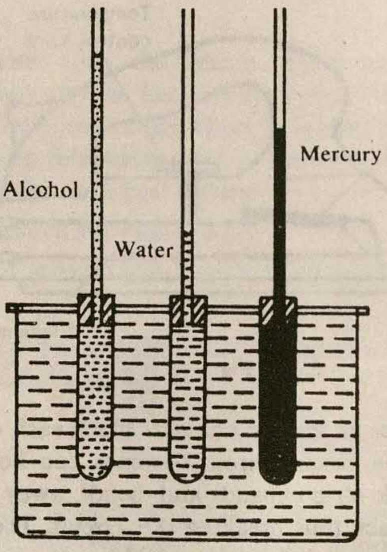


Fig. 7.13

Now gently heat the water in the beaker and keep it stirring all the time to ensure uniform temperature of the bath. It is found that alcohol expands the maximum and water the least (Fig. 7.13).

7.6 Measurement of Temperature

By the sense of touch one can estimate the temperature of a body, but with its help it is difficult to tell which body is at higher temperature than the other, if the difference of their temperatures is small.

Also the sense of touch is not always reliable as it depends upon the pervious condition of the hand. To measure the temperature of a body, we need an instrument called a **thermometer**.

Liquid Thermometer

Thermometer is an instrument specially designed to measure the temperature of a body. The most common form of a thermometer contains either mercury or alcohol. It is based upon the fact that increase in volume of a liquid is directly proportional to the *rise of temperature* and the initial volume of the liquid. It also depends upon the nature of the liquid. If the liquid and its initial volume is kept the same, then by measuring the increase in volume one can measure the change of temperature.

An ordinary thermometer consists of a stem having a uniform capillary tube with an expansion chamber at the upper end and a bulb containing mercury at the lower end. It has a scale engraved on it (Fig. 7.14a). It can be compared with the ordinary expansion apparatus as shown in Fig. 7.14b. The flask, containing most of the liquid, corresponds to the *bulb* and the uniform narrow tube with the *stem.*

Ordinary thermometers are suitable for use because

1. The bulb has thin walls and thus allows the heat to pass through it easily.
2. The stem is made of thick glass and is strong enough. It has a very narrow uniform bore because of which a small change in volume of the liquid in the stem causes a large movement of mercury in the stem. In other words, it makes the thermometer more *sensitive*.
3. The expansion chamber at the top allows the overflow of mercury to enter into it when per chance the thermometer is overheated.

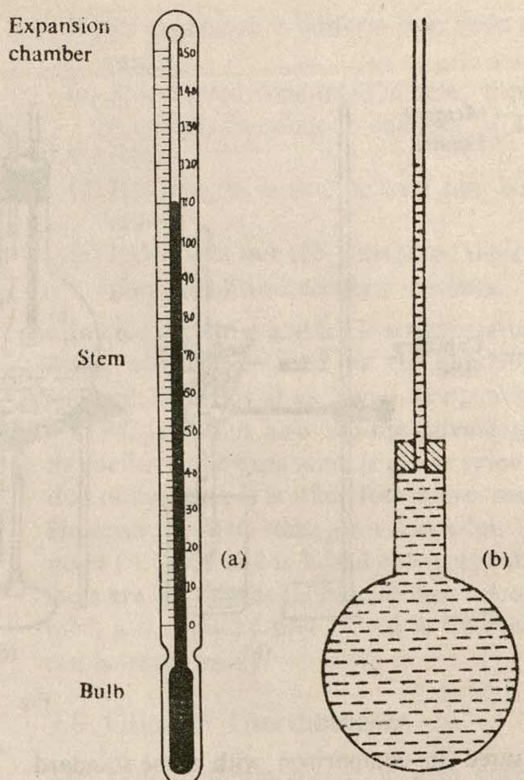


Fig. 7.14

How to Make Your Own Thermometer

Take a clean capillary tube with a uniform bore having a funnel at one end and a bulb at the other. The bore of the tube is so narrow that it is not possible to fill the bulb by simply pouring mercury in the funnel. Pour some mercury into the funnel (Fig. 7.15a) and dip the bulb into a hot water bath. Air inside the bulb expands and bubbles out through the mercury in the funnel. Cool the bulb by pouring water on it. The air inside contracts and some of he mercury is sucked in. By alternate heating and cooling, fill the bulb and the stem with mercury. Heat the bulb to a temperature slightly higher than the maximum temperature it is supposed to measure. While the bulb is still hot, break the funnel and seal the open end by rotating it over a small hot blowpipe flame. Allow the bulb to cool gradually. It is now ready for graduation.

Fixed Points

Like all other measurements, temperature is

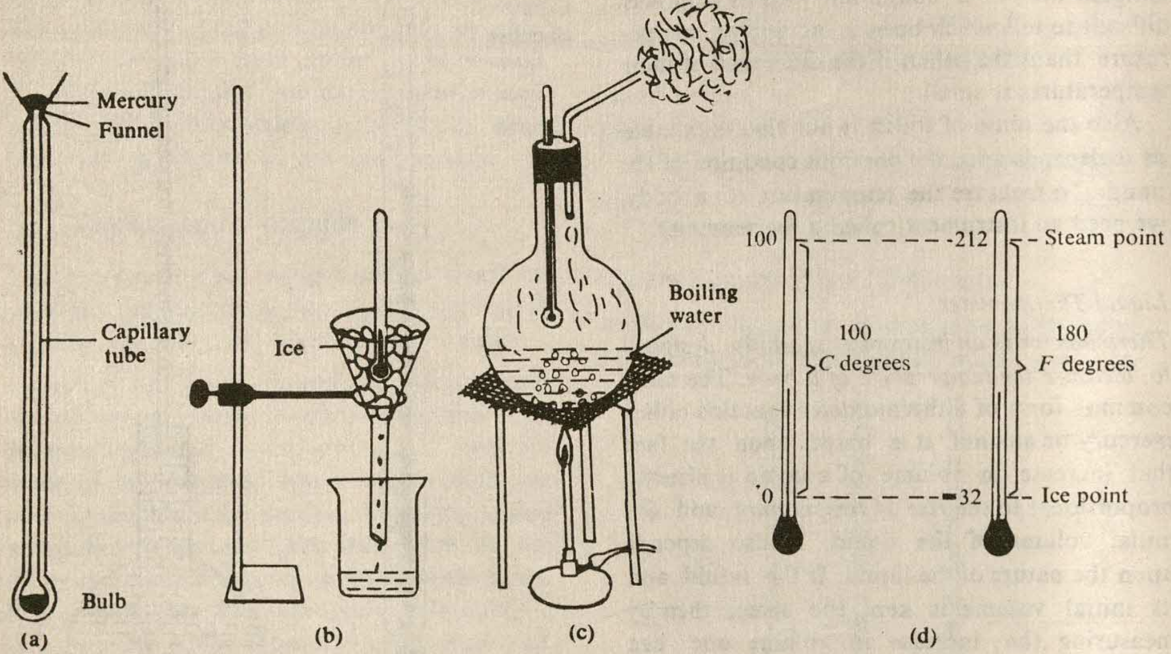


Fig. 7.15

measured in comparison with some standard. Two temperatures which are reproducible and non-variable are taken as *fixed points* for reference. These two are (a) **The Lower Fixed Point**, which is the melting point of pure ice at standard pressure and (b) **Upper Fixed Point** which is the temperature of steam produced at the boiling point of pure water at standard pressure.

Soluble impurities raise the boiling point of water and lower the melting point of ice. Increase of pressure raises the boiling point of water and lowers the melting point of ice. Hence, for standardization these factors should not be allowed to vary.

Activity 7. Hold a laboratory thermometer in a funnel containing small pieces of melting ice (Fig. 7.15b), till the mercury level becomes steady. The mercury thread should be just visible above the ice. Mark this level. Now boil some water in a flask over a burner (Fig. 7.15c). Hold the thermometer in the steam above the boiling water so that the mercury thread is just above the cork. Mark this level when it becomes steady. Under given conditions, i.e. if the ice were made of distilled water and the pressure were that at sea level, these two levels would be the two fixed points.

The two fixed temperatures are taken to be 0°C and 100°C and the distance between these two is then divided into hundred equal parts, each division representing a degree **Celsius** of temperature change. In this marking it is assumed that equal changes of temperature produce equal increases in volume of the liquid, and that the stem of the thermometer is uniform.

Another scale used in some countries is the Fahrenheit scale. On this scale the lower fixed point is 32°F and the upper fixed point is 212°F. The distance between the two fixed points is divided into 180 equal parts; each part is called a °F (degree Fahrenheit).

The proportionality relationship between the Celsius and Fahrenheit scales is shown in Fig. 7.15 (d) and is as follows

$$\frac{C}{100} = \frac{F-32}{180}$$

With the help of this equation, Celsius temperature can be converted into Fahrenheit and vice versa. Solving for F, we have

$$F=\frac{9}{5}C+32$$

and solving for C, we have

$$C=\frac{5}{9}(F-32)$$

EXAMPLE 1. Convert 122°F into °C,

Given $F=122$

To find $C=?$

Solution

As $$\frac{C}{100}=\frac{F-32}{180}$$

$$\therefore \quad C=\frac{5}{9}(F-32)=\frac{5}{9}(122-32)$$

$$=\frac{5}{9}\times 90=50^\circ\mathrm{C} \qquad \textit{Answer}$$

7.7 Sensitivity of a Thermometer

A thermometer is sensitive when even small changes in temperature can be noticed. Sensitivity can be increased by (a) increasing size of bulb; the initial volume is more and hence for the given rise of temperature increase in volume is more; (b) taking the stem of narrow bore so that for a given increase in volume the mercury thread will have to move a greater distance; and (c) using a liquid whose coefficient of expansion is high; in this respect alcohol is more suitable than mercury.

7.8 Liquids in Thermometer

Mercury is the most commonly used liquid in thermometers because:

(a) It remains a liquid over a wide range (from − 39°C to +357°C) of temperature, and hence can be used over most of this range.

(b) Its expansion is uniform over most of this range.

(c) It is a good conductor of heat; therefore, it quickly responds to changes of temperature.

(d) It is opaque; hence, its level can be read easily.

(e) It does not wet the glass stem; therefore it gives quick and accurate readings.

In cold countries and for low temperature readings, alcohol is used as the thermometric material; it freezes at as low a temperature as −117°C. Alcohol also has the advantage that its coefficient of expansion is about seven times that of mercury; it is therefore more sensitive. However, it wets the glass, has a low boiling point (+78°C) and is a bad conductor of heat; these are its disadvantages. When alcohol is used, it is coloured blue or red so that the level can be ready easily.

7.9 Clinical Thermometer

The clinical thermometer, is also called the doctor's thermometer as it is used for finding temperature of a human body. It contains mercury. Since it has no other purpose, the temperature range on the thermometer is short, usually 35 to 43°C (or 95 to 110°F). There is a mark at 36.5°C (or 98.4°F) on the stem indicating the normal temperature of a human body. The temperature is taken with it by placing its bulb under the armpit or under the tongue. The two readings, however, show a difference of about 0.5° Celsius, the armpit temperature being lower. It is preferable to use the thermometer by placing its bulb under the tongue of the patient.

The thermometer has a kink or constriction above the bulb (Fig. 7.16). When the bulb is placed under the tongue, mercury expands and forces its way up in the stem. When the thermometer is taken out of the mouth, the mercury

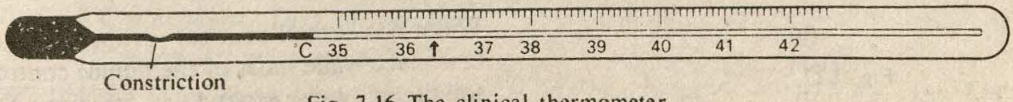
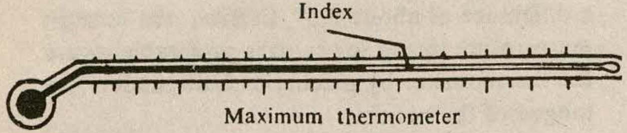


Fig. 7.16 The clinical thermometer

contracts and its thread breaks at the constriction. Because of this, the mercury in the stem stays where it is and its reading can be taken accurately even after some time. After use, the bulb is washed with fresh or lukewarm water and the thread is reset by giving the thermometer a jerk. It should not be sterilised by placing it in hot water, as the temperature of mercury will then rise above 43°C and the force of expansion of the mercury may even break the glass tube. The bulb should necessarily be thin, so that mercury inside the bulb may quickly respond to the temperature.

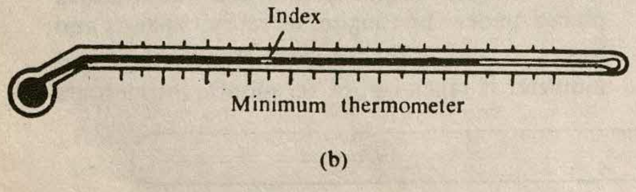
7.10 Other Thermometers

At times we want to know the highest or lowest temperatures attained during the day, but recorded at some later time. In an ordinary thermometer these temperatures may be attained at a time when we may not be looking at the liquid level. We therefore need a thermometer which can record these temperatures such that they can be read off at any convenient time. The need for continuous observation is avoided by a clever arrangement in these thermometers. The **maximum thermometer** uses mercury as the liquid. A small iron index with a spring attached to it holds the tube above the mercury in the stem (Fig. 7.17a). When mercury expands, the index is pushed up the stem but stays there when it contracts. The end of the index near the bulb registers the highest temperature reached.



Maximum thermometer

(a)



Minimum thermometer

(b)

Fig. 7.17

The **minimum thermometer** uses alcohol as the liquid and the index is inside the level of the liquid. When the temperature falls and alcohol contracts, its surface, acting as a stretched skin, pulls down the index. The index stays in position when the temperature rises and alcohol expands. The end of the index away from the bulb registers the minimum temperature reached. In both these thermometers, a magnet is used to reset the index.

7.11 Six's Maximum and Minimum Thermometer

The maximum and minimum thermometer serves a double purpose; to measure and record the maximum temperature during the day and the minimum temperature during the night. The bulb *A* (Fig. 7.18) contains the thermometric liquid alcohol, whose change in volume with temperature is primarily responsible for registering the minimum and maximum temperatures. Section *B* to *C* contains mercury; above *C* there is alcohol which partly fills the bulb *D*, leaving some space above it to allow for the expansion. When the alcohol in *A* expands due to rise in temperature, it pushes the mercury section down *B* which in turn pushes the steel index upwards above *C*. The index enables the maximum temperature reached during the day to be read on the scale marked along the limb. When the alcohol in *A* contracts due to fall in temperature at night, the mercury is drawn back pushing the steel index upwards above *B*. The index therefore gives the minimum temperature reached during the night, and it can be noted on the scale marked along this limb.

At any time of the day, mercury level in both the limbs is always the same and gives the room temperature.

7.12 Anomalous Expansion of Water

Water has several peculiar properties. In the first place while most of the liquids contract on solidifying, water expands on freezing. During

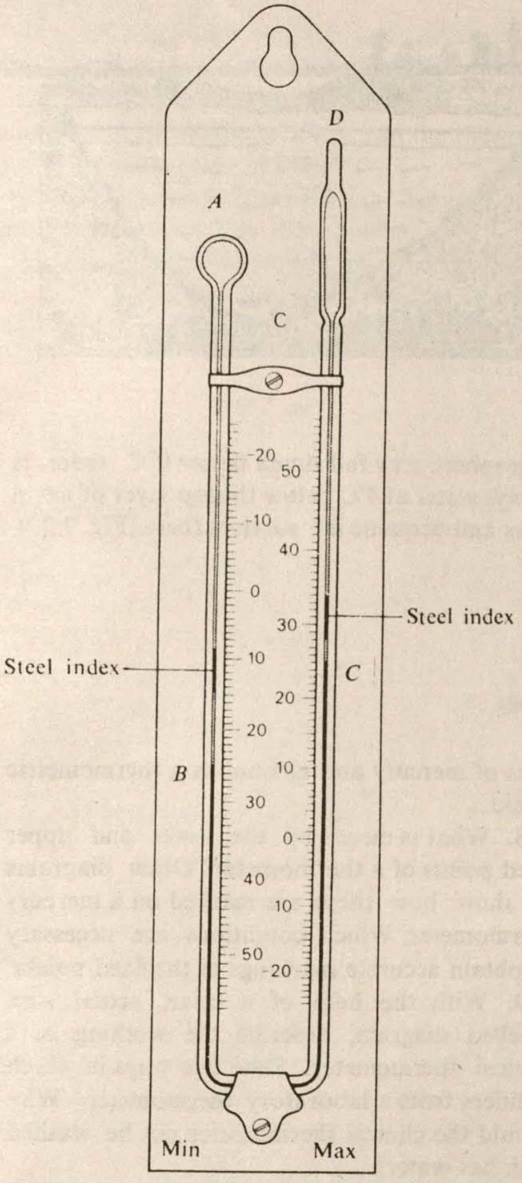


Fig. 7.18

frosty weather and at high altitudes when water in the pipes freezes, it expands and sometimes the pipes may even burst; also ice being less dense floats on water. Secondly when water is cooled, its volume decreases till 4°C and on cooling below 4°C it expands. *Thus for a given mass of water, its volume is the minimum at 4°C and its density is the maximum.*

Activity 8. Take a dilatometer which is a graduated bulb with a long neck. Add mercury to it so that it fills it upto 1/7th of its total volume. On heating, the glass expands and the volume of the space above the mercury increases; this increase is compensated by the expansion of mercury. As the expansion of mercury is seven times that of an equal volume of glass and its volume is 1/7th of the volume of glass, so the expansion of glass and mercury are equal.

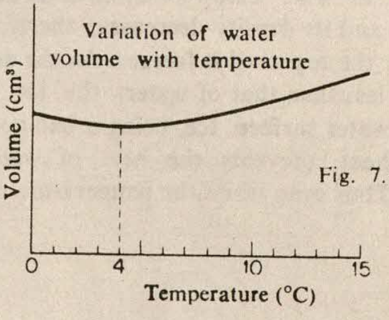


Fig. 7.19 (a)

Fill the space above mercury with water upto the level *a*. Cool the dilatometer; the level of water falls till 4°C and on further cooling it expands. Draw a graph of volume against temperature. It is as shown in Fig. 7.19a. It is evident from the graph that the volume of water is the minimum at 4°C.

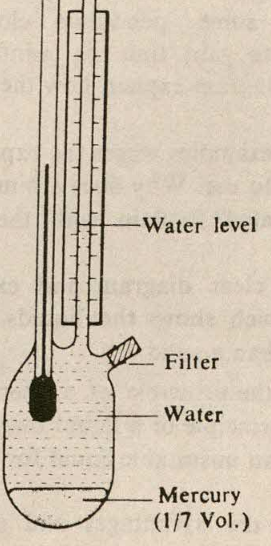


Fig. 7.19 (b)

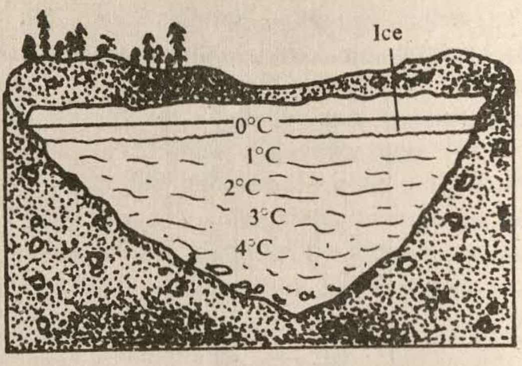


Fig. 7.20

This unusual expansion of water plays an important part in the preservation of aquatic life during cold weather where the temperature of a lake or pond falls several degrees below 4°C. As the temperature of the atmosphere falls, the top surface of water cools and contracts; being denser it goes down to the bottom and water from below comes up to take its place. Thus *convectional currents* are set up and circulation of water is caused till the whole of the water is at 4°C. Below 4°C, water at the top expands and its density decreases, therefore it stays at the top until it freezes. As the density of ice is less than that of water; the ice floats at the water surface. Ice, being a bad conductor of heat, prevents the heat of water to escape. Thus even when the temperature of the atmosphere may fall much below 0°C, there is always water at 4°C below the top layer of ice in lakes and acquatic life survives there (Fig. 7.20).

QUESTIONS

1. Give two examples in which expansion of a solid is a disadvantage, and state how the difficulty is overcome.

2. A square brass plate of size 20 cm, with a circular whole of diameter 8 cm in the middle is heated. How will its (a) length; (b) area; (c) volume; (d) mass; (e) hole diameter and (f) density changes?

3. Why do some pendulum clocks and watches tend to gain time in winter? With the help of a diagram explain how the problem is overcome.

4. Give two examples where the expansion of solids is put to use. Why does a bimetal strip curve when heated? Explain with the help of a diagram.

5. Draw a clear diagram and explain an experiment which shows that liquids generally expand more than a solid.

6. What is the principle of a thermometer? What is the principle of a liquid thermometer? Why is water an unsuitable liquid for use in a thermometer?

7. Compare the advantages and disadvantages of mercury and alcohol as a thermometric liquid.

8. What is meant by the lower and upper fixed points of a thermometer? Draw diagrams to show how these are marked on a mercury thermometer. Which conditions are necessary to obtain accurate markings of the fixed points?

9. With the help of a clear, actual size, labelled diagram, describe the working of a clinical thermometer. State two ways in which it differs from a laboratory thermometer. Why should the clinical thermometer not be washed with hot water?

10. Draw a clear diagram and explain how a minimum thermometer works. Why is alcohol used in this thermometer but not in a maximum one?

11. When the bulb of a laboratory thermometer is suddenly placed into hot water, it is observed that the mercury level in the stem first falls slightly and then rises rapidly. Explain why this happens.

12. State two ways in which the construction of a mercury thermometer can be altered to

increase sensitivity.

Out of mercury, alcohol and air thermometers, which is the most sensitive? Why?

13. Why is a clinical thermometer also a maximum thermometer? How can the thermometer be made quick-reading?

14. The distance of separation between the ice and steam point in a thermometer is 15 cm:

(a) What temperature will the thermometer read when the mercury level is 6.0 cm above the ice point?

(b) Where will the mercury level be when the thermometer reads 80°C?

15. A glass jar containing water is left in the open on a frostly night. It is observed that freezing starts at the *top* of the water, and the jar might even *break* sometime later. Explain these observations with reference to the two words in italics.

8

Paths of Heat

Heat is transmitted from one body to another or along parts of the same body in various ways, some of which are slow and indirect, and others are fast and direct. A knowledge of the modes of transmission of heat is essential to reduce big losses of heat during transit, and to facilitate dissipation of heat to prevent overheating. Hot water storage tanks and pipes are covered with a layer of plaster mixed with asbestos to reduce loss of heat. Cars are provided with radiators which allow heat to escape fast and prevent the overheating of the engine. Let us study one by one the different ways by which heat can be transmitted from one place to another.

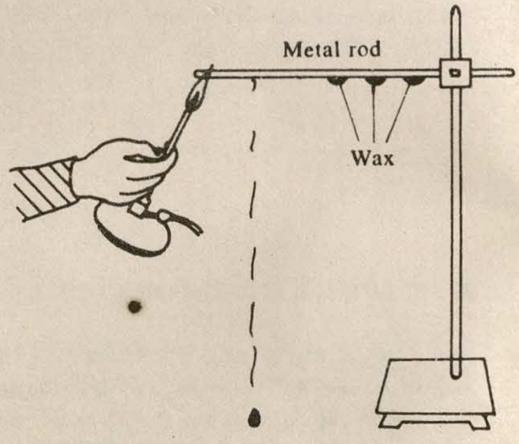


Fig. 8.1

8.1 Conduction

Activity 1. Clamp a metal rod horizontally in a retort stand. Cut small studs of wax from a candle and fix them on the rod along its length as shown in Fig. 8.1.

Heat one end of the rod. You will notice that the wax pieces fall off one by one from the heated end. As heat reaches a wax piece, it melts and falls down. Thus heat energy is transmitted through a metal from the hot end towards the cold end and this process of transfer of heat is called *conduction.*

You know that in solids, molecules vibrate about their fixed positions. Their speed of vibration increases with the increase of temperature. If one end of a metal rod is heated, the molecules at that end begin to vibrate vigorously They in turn cause the neighbouring molecules to vibrate vigorously. In this manner the increased vibration or heat energy is transmitted from molecule to molecule from the hot to the cold end of the metal rod till the other end also becomes hot.

Conduction *is that mode of transfer of heat in which heat is transmitted from molecule to molecule from the hot to the cold end; the molecules themselves do not go from one end to the other.*

8.2 Good and Bad Conductors

Activity 2. Hold one end of an iron rod in hand and put the other end in a candle or a bunsen burner flame. After some time the other end becomes too hot to hold. Repeat the experiment with a similar copper rod. It is observed that the heat reaches the other end much more quickly. If a glass rod is used instead, the other end remains comfortably cold while the end in fire may become red hot.

The experiment shows that there is a wide difference in the ability of various materials to conduct heat. Materials like copper, aluminium and brass which conduct heat quickly are called **good conductors**. On the other hand materials like glass, cork and wood which conduct heat very slowly are called **bad conductors** or **insulators**. Most metals are good conductors of heat. Silver and copper are the best conductors. Copper conducts heat about eight times faster than steel.

In general, thermal conductors are also good conductors of electricity and insulating materials are equally effective thermally and electrically.

Uses of Good and Bad Conductors

Both good and bad conductors have their uses. Frying pans, kettles and other cooking utensils are made of metals like brass, aluminium and iron. Copper, though a very good conductor, is not used for cooking utensils because it reacts with food to form poisonous materials. The 'bit' of a soldering iron is made of copper; when its tip comes into contact with the material to be soldered, heat rapidly flows from other parts of the bit to the tip so that its temperature always remains higher than the melting point of the solder.

Insulators have comparatively wider applications. Handles of kettles, soldering iron and pans, etc. are often made of bad conductors like plastic and wood so that they do not heat up and can be held comfortably.

Air and all other gases are bad conductors of heat. Wool is warmer than cotton because it is full of tiny pockets of air enclosed by the fibres of the material. In winter, a string vest is preferred over an ordinary one even when it is full of holes. This is because when a shirt is worn over it, air is trapped in the holes between the shirt and the vest. Air being a very poor conductor does not allow the heat of our body to escape to the atmosphere.

Heat losses by conduction through the walls of an oven are minimised by constructing ovens of double walls and packing the space between them with glass wool. Glass wool is a very poor conductor and is also non-inflammable. *The non-conducting material used to reduce the escape of heat is called* **lagging**. Another example of lagging is the covering of water pipes exposed to atmosphere with strips of felt or jute to prevent the loss of heat from water inside. This prevents freezing of water during winter.

Miner's Safety Lamp

Activity 3. Place a wire gauze about 5 cm above a bunsen burner. Turn on the gas and light it under the gauze. It is observed that for some time the flame does not go up the gauze. This is because the heat reaching the gauze is conducted away to other parts of it (Fig. 8.2a).

Turn off the gas and allow the gauze to cool. Turn on the gas again but now light it above the gauze. It is noticed that as in the previous case the flame continues to burn above the gauze and does not burn underneath it (Fig. 8.2b).

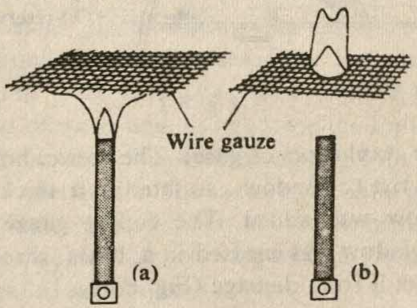


Fig. 8.2

Miner's safety lamp as devised by Sir Humphry Davy in 1813 is based upon the principle illustrated above. In coal mines methane, which is an inflammable gas, is often found.

When a mixture of methane and air comes into contact with the naked flame of candles used at that time, it explodes. By using the Davy safety lamp, which consists of a simple oil burner surrounded by a wire gauze, the number of mishaps in the mines were highly reduced. The gauze rapidly conducts the heat of the flame and the temperature outside is never high enough to cause explosion of gases. The gauze, however, gives rise to shadows, so later on a thick glass window was added. The copper gauze above the window was encased in a brass shroud to protect it from damage (Fig. 8.3).

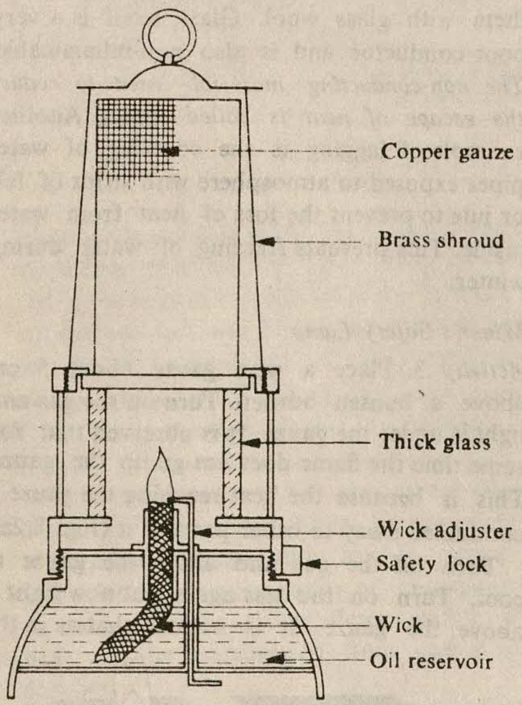


Fig. 8.3

Conduction of Heat through Liquids

Activity 4. Wrap a piece of ice with a wire gauze so that both together sink in water. Place the combination at the bottom of a boiling tube and fill it with water. Hold a bunsen burner flame near the top of the boiling tube. It is found that the water at the top soon begins to boil but the ice below has not melted fully (Fig. 8.4). If the experiment is repeated by heating the tube from below with ice floating on top, the ice melts quickly.

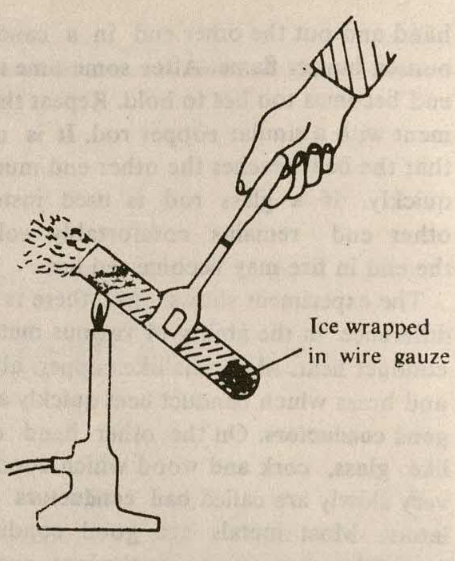


Fig. 8.4

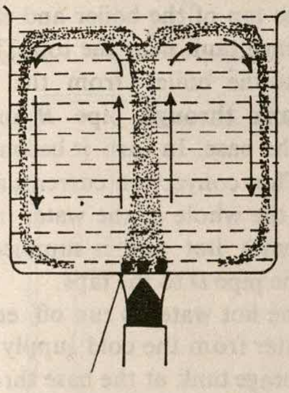
All liquids except mercury are bad conductors of heat. However, it is common experience that a liquid heated from below heats up easily; heat flows upwards easily. There must therefore be a phenomenon other than conduction which causes heating in liquids. This phenomenon is called *convection.*

8.3 Convection in Liquids and Gases

In conduction there is no movement of the conducting material. In convection, however, a hot gas or liquid moves to a cooler place where it gives up its heat. It then returns to the source of heat to be warmed up again.

Activity 5. Fill a beaker with water and drop a large crystal of potassium permanganate at its bottom in the centre with the help of a glass tubing. Close the mouth of the tube with a finger and then remove it together with the coloured water it contains. In this way, the potassium permanganate crystal is added without much disturbance. Heat the bottom of the beaker with a very small gas flame as shown in Fig. 8.5.

It is observed that coloured water rises from



Purple Potassium permanganate crystals

Fig. 8.5

the place where the heat is applied. On reaching the top it spreads out and descends down along the sides of the beaker. As the water at the bottom is heated it becomes lighter and rises up. As it reaches the cooler upper layers it gives its heat to the cold water and, becoming cold again, descends along the side of the beaker. Currents so formed are known as **convectional currents.** This process continues till the whole of the water gets heated.

Activity 6. Convection in air is shown by using an apparatus as shown in Fig. 8.6. It consists of a rectangular box with two wide glass tubes projecting from the top and having a removable glass front.

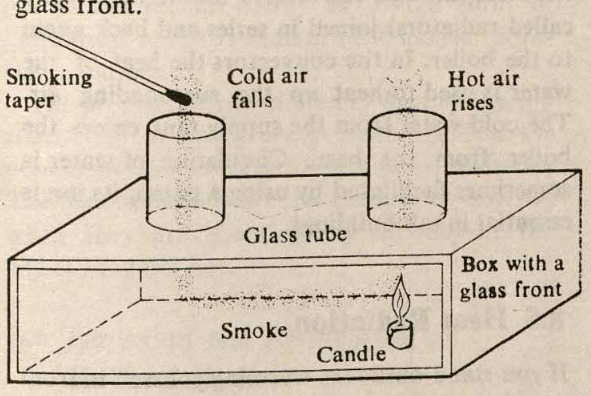


Fig. 8.6

Place a small lighted candle at the base of one of the tubes and hold a smouldering taper at the top of the other tube. Smoke is seen entering down the tube over which the smouldering taper is held and rising above the candle and leaving from the tube above it.

Air above the candle becomes warmer and *lighter* and moves up; its place is taken by fresh air sucked in from the top of the other tube. Hence **convection** *is a mode of transfer of heat in which heated particles of a fluid go from one place to the other.* As mass movement of particles is not possible in solids, convection cannot take place in them.

Convection currents in a refrigerator are set up exactly in the opposite way. The freezing chamber and the ice box are at the top. The air coming in contact with them gets cooled and becomes denser. The cold dense air then moves down and its place is taken by warmer air from below. The convectional currents thus set up keep the foodstuff cold.

8.4 Applications of Convection

1. *Land and Sea Breezes*

At places near the sea, during the day the breeze generally blows in from the sea to the land and at night it blows from the land to the sea. These are called sea and land breezes respectively.

At coastal places during the day the land gets hot quicker than the sea. This is because the specific heat capacity of land is much less than that of water and also because the top hot layer of water is constantly mixing with the bottom cooler layers. The air over the land gets heated, expands and rises above. Its place is taken by cooler air blowing in from the sea. This is called **sea breeze.**

At night, the land cools very rapidly while the sea shows practically no change of temperature and consequently acts as a large reservoir of heat. The air above the sea is now comparatively warmer and becomes lighter. It rises up and cold air from over the land blows out to the sea. Because of the sea and land breezes, the temperature of coastal places remains moderate. It is not very hot during the day nor very cold at night.

2. *Ventilation*

Ventilation is a practical example of the use of convection currents to keep the insides of rooms cool and fresh. The air we breathe out is warmer and rises up while its place is taken by fresh air coming inside from the windows; ventilators at the top provide outlet for the stale and warm air. Ocean currents and trade winds are examples in nature of large scale convection currents set up due to the difference of temperature in air and water.

3. *The Domestic Hot Water Supply*

Hot water system in many hotels and houses is based on the principle of convection. It essentially consists of a *boiler*, a *hot water storage tank* and a *cold supply tank* interconnected by pipes as shown in Fig. 8.7.

When the fire below the boiler is lit, water in it becomes hot and light. It rises up the pipe *A* from the top of the boiler and enters the hot water storage tank near the top. The cold water descends to the boiler from the base of the storage tank through pipe *B* and enters the boiler at the base. In turn it becomes hot and rises up. Thus convection currents are set up and gradually the whole of the water in the storage tank becomes hot and is supplied from there through the pipe *D* to the taps.

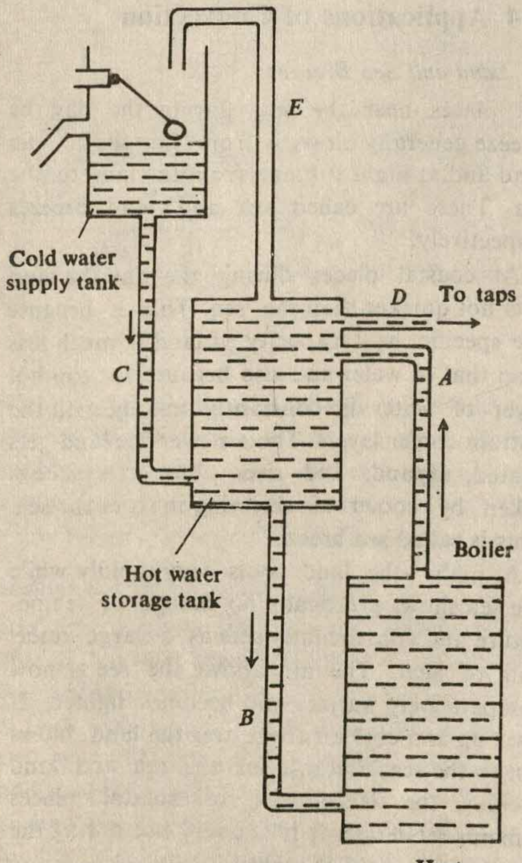


Fig. 8.7

When the hot water is run off, equal volume of cold water from the cold supply tank enters the hot storage tank at the base through pipe *C*.

The expansion pipe *E* is a safety device. If per chance, hot water is not taken out from the taps and the fire below the boiler keeps on burning, then steam and boiling water from the hot water storage tank are discharged harmlessly through *E* to the cold water supply. The expansion pipe also allows the dissolved air to escape, otherwise it may cause air locks in the pipes.

4. *Heating a House*

The central heating system (Fig. 8.8) is similar to a domestic hot water supply system, except that there is no hot water storage tank.

The boiler is generally situated in the basement and the cold water supply tank is located at the top of the building. Water in the boiler becomes hot and leaves from a pipe at the top. It passes through convectors (often incorrectly called radiators) joined in series and back again to the boiler. In the convectors the heat of the water is used to heat up the surrounding air. The cold water from the supply tank enters the boiler from the base. Circulation of water is sometimes facilitated by using a pump; its use is essential in tall buildings.

8.5 Heat Radiation

If you stand outdoors warming yourself in front of a fire on a winter day, the heat you receive certainly does not come to you by conduction through the air or the ground, since both of these are cold. Neither do you receive heat by convection since hot air rises up. You receive

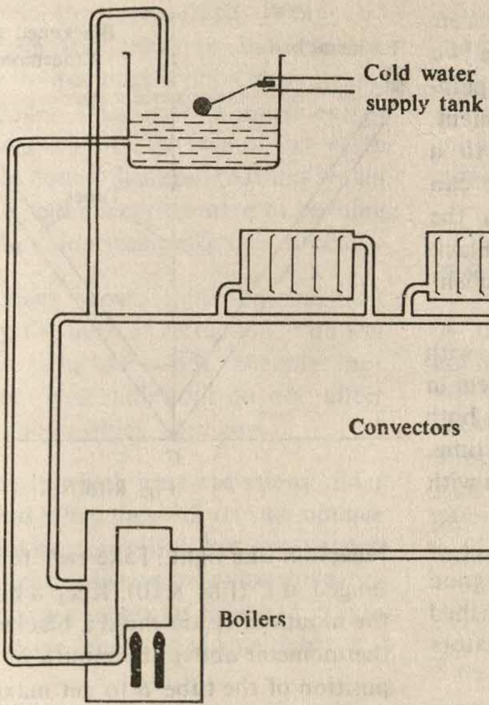


Fig. 8.8

heat by a third way, in which heat energy is transferred from one body to another in exactly the same manner as light. This third way is called *radiation*.

We receive energy from the sun as radiations even when there is a vacuum of about 150 million kilometres in between. Only a small part of this radiant energy is in the form of light; most of this is radiant heat named *infra-red* radiations.

The process of transmission of heat by energy transfer from one place to another without the need of an intervening medium is called **radiation.** The heat radiations are not themselves hot but when they are absorbed by an object, the object becomes hot.

8.6 Emission and Absorption of Radiant Heat

The rate at which a body radiates heat depends upon (a) its surface area—greater the surface area, more is the loss of heat by radiation; (b) temperature of the surface—hotter surfaces radiate more heat than cooler ones and (c) the nature of the radiating surface.

Activity 7. Take two identical tin cans; paint one of them black and keep the other shining from outside. Fill them half with water, cover them with cardsheets which hold a thermometer, and place them on a table in the open under direct sunlight. (This ensures that infra-red

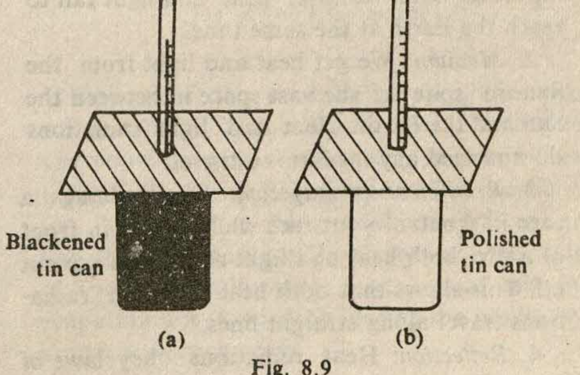


Fig. 8.9

radiations from the sun are also striking them directly.) Note the mercury levels in the two thermometers which would show the temperature of water at the beginning of the experiment. This is same in both cases (Fig. 8.9). In a few minutes, the thermometer in the black can records a greater rise in temperature than the one in the polished can. This shows that black surfaces are good absorbers of heat and polished surfaces are bad absorbers of heat.

Now replace the water in both the cans with equal volume of hot water and place them in the shade. Note the temperatures given by both the thermometers after short intervals of time. It is noticed that the water in the can with blackened surface cools faster than the water in the can with polished outer surface. This experiment shows that black surfaces are good radiators of heat. In other words polished surfaces are good reflectors but poor radiators of heat.

The back of refrigerators and hot plates are coloured dull black to radiate heat effectively. In summer white and light-coloured clothes are preferred as white surfaces are bad absorbers of heat and in winter dark clothes feel warmer as dark surfaces are good absorbers of heat.

8.7 Light and Heat Radiations

Heat and light radiations resemble in various ways; in fact they are the members of the same family.

1. *Velocity*: Heat and light radiations travel with the same speed which is 3×10^8 m/s. During total solar eclipse, heat and light fail to reach the Earth at the same time.

2. *Medium*: We get heat and light from the Sun in spite of the vast space in between the Sun and the Earth. Heat and light radiations do not need any medium to travel.

3. *Rectilinear propagation*: On holding a card in front of your face while sitting in front of a fire, both heat and light radiations are cut off. This shows that both heat and light radiations travel along straight lines.

4. *Reflection*: Heat radiations obey laws of reflection like light. Take two tubes A and B hinged at C (Fig. 8.10). Keep a hot metal ball at the mouth of A and hold a blackened bulb of a thermometer above the mouth of B. Adjust the position of the tube B to get maximum rise of temperature in the thermometer. It is found that at this a stage the two tubes are inclined equally to the normal at C. Then $\angle i = \angle r$.

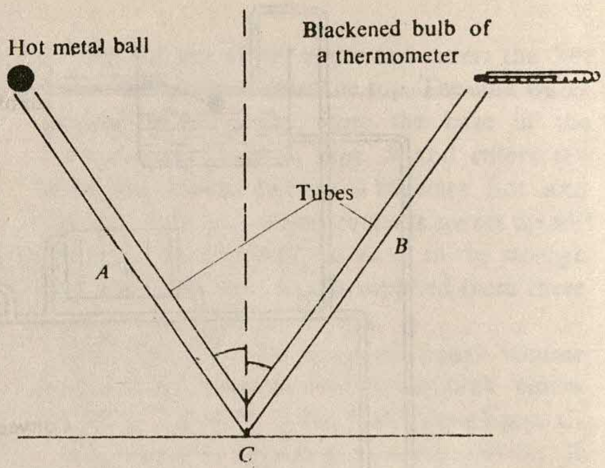


Fig. 8.10

5. *Refraction: Activity* 7. On a clear sunny day hold a magnifying glass (converging lens) in one hand and a piece of carbon paper in the other just below the lens. Move the lens closer or further away to form a small bright spot on the paper (Fig. 8.11). If you hold your hand

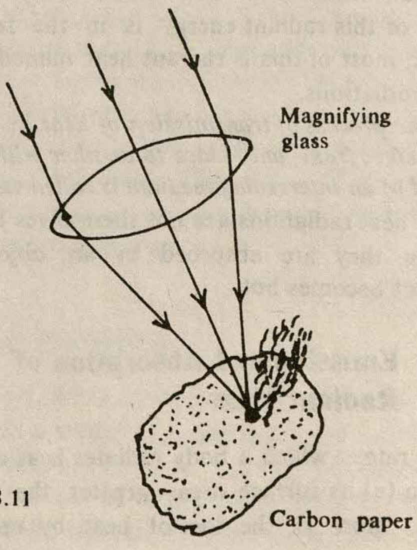


Fig. 8.11

steady for a while, the paper starts fuming. It shows that all the heat reaching the lens has been brought to focus at a point and burns a hole into the paper. Imagine how much energy must be reaching the total surface of the earth each day; it has been calculated that this would be equal to the heat energy released by burning more than 100 million million tonnes of coal.

This experiment shows that heat and light radiations obey the laws of refraction. You will notice that the lens does not become hot which shows that heat radiations do not affect the medium through which they pass.

The only way in which heat radiations differ from light is that when they fall on an opaque object it does not become visible but may become hot. Heat and light radiations are electromagnetic waves, the wave length of infra-red rays is more than the wave length of visible light.

8.8 Cooling System in Cars

Engines of motor cycles and scooters become hot as they run; cooling is caused by the surrounding air which comes into contact with the engine and carries away the heat.

In case of motor cars and other heavy vehicles, the engine *E* (Fig. 8.12) is surrounded by a jacket through which water circulates. The water around the engine becomes hot and light, it rises up and is made to trickle down the radiator pipes *R*. An exhaust fan *F* behind the radiator sucks in air from outside and helps the water in the radiator to cool quickly.

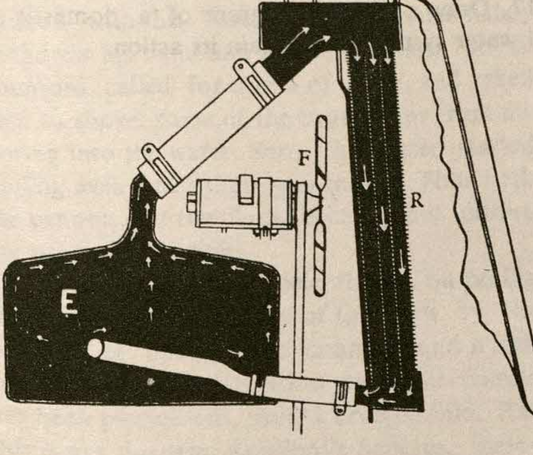


Fig. 8.12

8.9 Thermos Flask

A thermos flask is a household appliance in common use to keep things warm or cold. It consists of a double-walled flask encased in a metallic case and is separated from it by cork supports. Air between the walls is envacuated and the inner surface of the outer wall and outer surface of the inner wall are silvered. The mouth is closed by a cork (Fig. 8.13).

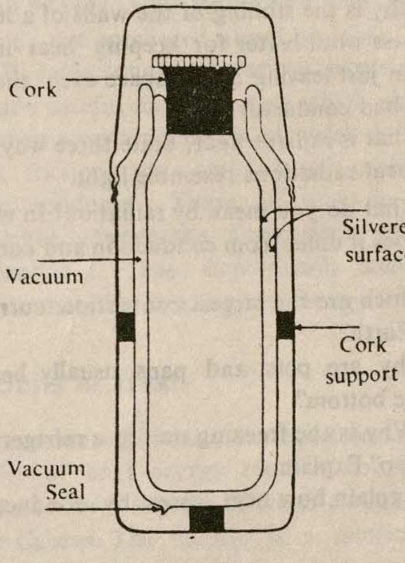


Fig. 8.13 Thermos flask.

Because of the vacuum between the two walls, flow of heat either way by conduction and convection is considerably minimised as both conduction and convection need particles for their transfer. Since polished surfaces are bad absorbers and good reflectors of heat, loss of heat by radiation is reduced. Loss of heat by evaporation is stopped by closing the mouth by a nonconducting cork.

QUESTIONS

1. One end of a brass rod is hotter than the other. Describe in terms of the kinetic molecular theory the way in which heat travels from the hot end to the cold. Name the process of heat transfer.

2. Describe an experiment to compare the thermal conductivities of different materials. Name three good and three bad thermal conductors.

3. Describe an experiment and draw a clear diagram to show that water is a poor conductor of heat. How then does the water get heated quickly when a container full of water is kept over a burner?

4. What causes heated air and water to undergo convection?

5. Why is the stuffing of the walls of a house with glass wool better for keeping heat in or out than just leaving an air space even though air is a bad conductor?

6. What is radiant heat? State three ways in which heat radiations resemble light.

7. What do you mean by radiation? In which ways does it differ from conduction and convection?

8. Which are the largest convection currents on the Earth?

9. Why are pots and pans usually heated from the bottom?

10. Why is the freezing unit in a refrigerator at the top? Explain.

11. Explain how heat losses by conduction, convection and radiation are reduced in a thermos flask.

12. Explain why (a) A stone floor feels cold to bare feet in winter but a carpet in the same room feels comfortably warm; (b) A blanket wrapped around our body in winter keeps us warm, but helps a block of ice not to melt; (c) If rods of iron and copper are held in hand and their other end placed over a fire, the tip of the iron rod becomes red-hot while that of the copper rod does not seem to glow.

13. When a glowing cigarette is placed in an ashtray, the smoke is seen to curl upwards. Explain why this happens, and show with the help of a diagram how this fact can be used in ventilation of rooms.

14. Distinguish between conduction and radiation of heat. Describe an experiment to show that a dull black surface is a better absorber of heat than a polished one. Give two ways by which heat lost by a body can be assisted and show how this is achieved in one practical example.

15. Describe Davy's safety lamp, and explain what happens when it is surrounded by an inflammable mixture of gas and air.

16. Draw a labelled diagram of a Dewar (or thermos) flask, and explain the principles on which its action depends.

17. Draw a labelled diagram of a domestic hot water system and explain its action.

9

Measurement of Heat

9.1 Nature of Heat

If you hold an iron rod near one end, and put the other end in the fire, heat seems to flow along the rod past your hand. It is not surprising that for many years scientists believed that heat was an invisible weightless fluid called 'caloric'. According to the caloric theory, the heat fluid runs from hot bodies into cold ones. However, this hypothesis was unsatisfactory in various ways. For example, if heat is a fluid, where does it come from when you rub your hands together? Both hands become hot, and nothing cools down. It will be worthwhile to mention here the findings of Count Rumford towards the end of eighteenth century. A brass cannon was being bored at Munich and one of the workmen carelessly touched the cannon with his bare hand. He immediately withdrew his hand and found a blister on it. Rumford called for a pail of water, and asked men to shovel some of the brass chips from the boring into the water. Soon the water started boiling even when there was no fire. Thus both the cannon and the chips became hot during the process of boring.

According to the caloric theory, on boring the caloric is squeezed out of the chips by the pressure of boring. The cannon gains it and becomes hot. The chips from whom the caloric has been pressed out, should become cold. But this is not the case. Rumford's findings, therefore, confirmed that there is no such thing as caloric. As far as he could see, any amount of heat could be obtained by maintaining *motion* against friction.

About 50 years after Rumford's time, people were still not convinced about his ideas. Then James P. Joule conducted various experiments and made careful measurements which showed that, when a certain amount of work is done against friction, the same amount of heat is always produced. There is thus an exact equivalence between the work done and the heat produced. These experiments convinced scientists that heat is a form of energy.

9.2 Units of Heat

Heat is measured in calories. One **calorie** is the quantity of heat energy required to raise the temperature of one gram of water through one degree Celsius. The calorie is a metric unit. You would have probably heard of calories in connection with food, but the food calorie is not the same unit. When you count the calories in food you are using kilocalorie (or Calorie, spelt with Capital C) which is equal to 1000 calories.

1 Calorie or 1 kilocalorie = 1000 calories

1 **Calorie** is the quantity of heat required to raise the temperature of 1 kilogram of water through one degree Celsius.

Modern measurements give energy equivalence of heat. According to these, equivalence is named as Joule's Mechanical Equivalent of Heat. Thus 4200 J of energy is required to raise the temperature of 1 kg of water through 1 degree C or 4.2 J of energy is needed to raise the temperature of one gram of water through one degree C.

Thus 4.2 J = 1 cal
or 1 J = 0.24 cal

And 4200 J = 1 kilocalorie or 1 Calorie.

9.3 Specific Heat Capacity

If we add equal masses of aluminium, copper and iron heated to 100°C in equal quantities of water contained in three similar separate containers, it is found that the final temperature of the mixture is the highest for aluminium and the least for copper. This shows that the quantity of heat in aluminium is more than that in an equal quantity of brass or copper heated to the same temperature. It is the least in copper. This property is called the **specific heat capacity** of a substance and is defined as *the quantity of heat required to raise the temperature of unit mass of that substance through one degree.* The symbol for specific heat capacity is *c*. (Unfortunately this is also the symbol for the speed of light in vacuum or air.)

The specific heat capacity of water is 4200 J/kg °C. This means that 4200 J of heat is required to raise the temperature of 1 kg of water through 1 degree Celsius. The specific heat for aluminium is 910 J/kg°C; for copper it is 390 J/kg°C.

The following table gives the specific heat capacity of a few commonly used substances.

Name	*c in J/kg°C*	*Name*	*c in J/kg°C*
Lead	130	Glass	670
Mercury	140	Rock	840
Brass	380	Rubber	1890
Copper	390	Ice	2100
Iron	470	Methylated spirit	2400
Aluminium	910	Water	4200

Water has a very high specific heat capacity, because of which it is extremely useful as a cooling agent, for example in the cooling system of an automobile. A hot water bottle will stay warm much longer when filled with water than when it is filled with any other liquid. Also ocean and lakes remain at a relatively constant temperature because water can absorb large quantities of heat without undergoing large temperature changes.

9.4 Heat Capacity

Another term which is commonly used in the measurement of heat is the **heat capacity** of a body which is defined as *the quantity of heat required to raise the temperature of the body through 1 degree Celsius.*

Let the mass of the body be *m* and its specific heat capacity be *c*. According to the definition, unit mass of the substance needs *c* amount of heat to raise its temperature through 1 degree C; for *m* units of its mass it will need *mc* amount of heat.

Hence heat capacity = mc J/°C

9.5 Formula for Quantity of Heat *Q*

Suppose *m* kg of a substance of specific heat capacity *c* is heated through Δt°C. According to the definition of *c*, unit mass of the substance for 1°C rise of temperature needs *c* Joules of heat. Then *m* kg of the substance for 1°C rise of temperature will need *mc* Joules and *m* kg of the substance for Δt rise of temperature will need $mc\,\Delta t$ Joules.

Hence $Q = m \times c \times \Delta t$ Joules

or Quantity of heat transferred = mass × sp.ht. capacity × change of temperature

EXAMPLE 1. 500 g of hot water at 60°C is kept in the open. Its temperature falls to 40°C in 3 minutes. Calculate the rate of loss of heat energy to the surroundings by the water (*c* of water = 4200 J/kg°C)

Given $m = 500\text{ g} = 0.5\text{ kg}$
$c = 4200\text{ J/kg °C}$
$\Delta t = 60 - 40 = 20\text{°C}$
time $=$ 3 minutes

To find $\dfrac{Q}{\text{time}} = ?$

Solution Since $Q = mc\Delta t$

$\therefore$ $Q = 0.5 \times 4200 \times 20 = 42{,}000\text{ J}$

$\dfrac{Q}{\text{time}} = \dfrac{42{,}000}{3} = 14{,}000\text{ J/min.}$

Answer

EXAMPLE 2. If a block of copper of specific heat capacity 420 J/kg°C has a mass of 200 g and is heated from 20 to 200°C, calculate the amount of heat needed.

Given $m = 200\text{ g} = 0.2\text{ kg}$
$c = 420\text{ J/kg°C}$
$\Delta t = 200 - 20 = 180\text{°C}$

To find $Q = ?$

Solution Since $Q = mc\Delta t$

$\therefore$ $Q = 0.2 \times 420 \times 180$
$= 15{,}120\text{ J}$ *Answer*

9.6 Principle of Calorimetry

Activity 1. Pour 100 g of hot water at 80°C into 200 g of cold water at 20°C contained in a light aluminium can. Stir the contents with a thermometer and note the maximum steady temperature reached. This is found to be 40°C. It is assumed that no heat is lost to or gained from the atmosphere.

Heat lost by hot water $= mc\Delta t$
$= 0.1 \times 4200 \times (80 - 40)$
$= 420 \times 40 = 16{,}800\text{ J}$

Heat gained by cold water $= 0.2 \times 4200 \times (40 - 20)$
$= 840 \times 20 = 16{,}800\text{ J}$

Thus Heat lost = heat gained

This principle, known as the principle of calorimetry, holds good if there is no loss or gain of heat to the surroundings and the contents do not chemically interact with each other.

9.7 Determination of Specific Heat Capacity of a Solid

Activity 2. Heat the solid, say an iron ball, in boiling water or take a hypsometer and place it on a tripod stand. Put some quantity of solid (lead shots, copper chips or iron nails) into the tube of the hypsometer and fix a thermometer in it so that its bulb is surrounded by the solid. Heat the hypsometer with a bunsen burner or a spirit lamp (Fig. 9.1).

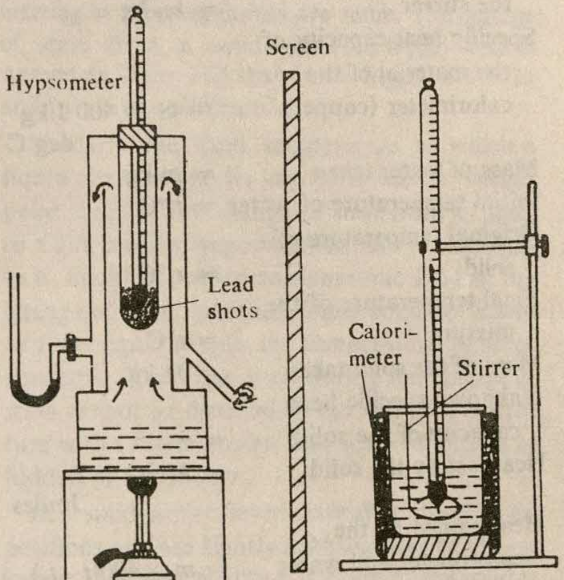


Fig. 9.1

Take a calorimeter with a stirrer and find its mass. Fill the calorimeter about half with water and weigh it again. From it work out the mass of the water taken. Note the temperature of the water and the calorimeter preferably with a half degree thermometer.

When the thermometer in the hypsometer shows a constant temperature, wait for about 5 minutes to ensure that the whole of the solid has attained this steady temperature. Note the temperature of the hot solid. Transfer the solid immediately into the calorimeter. (In case of an iron or brass ball being heated in boiling water, give a jerk to the ball, when it is just above the boiling water and then immediately transfer it to the water in the calorimeter.)

Cover the calorimeter and stir its contents to ensure uniform temperature throughout. When the thermometer shows a steady maximum temperature for a minute or two, note it. This is the final temperature. Remove the lid and then the thermometer and see that no water drops remain sticking to the thermometer. Weigh the calorimeter and its contents and from it calculate the weight of the solid added.

Mass of the calorimeter along with the stirrer $= m_1$ kg

Specific heat capacity of the material of the calorimeter (copper) $= c_1 = 400$ J/kg deg C

Mass of water taken $= m$ kg

Initial temperature of water $= t_1$°C

Original temperature of solid $= t_2$°C

Final temperature of the mixture $= t$°C

Mass of the solid taken $= M$ kg

Unknown specific heat capacity of the solid $= c$

Heat lost by the solid $= Mc(t_2 - t)$ Joules

Heat gained by the calorimeter and water $= m_1 \times 400(t - t_1) + m \times 4200(t - t_1)$
$= (400m_1 + 4200m) \times (t - t_1)$ Joules

According to the principle of heat exchanges:

Heat lost = heat gained

$$Mc(t_2 - t) = (400m_1 + 4200m)(t - t_1)$$

$$c = \frac{(400m_1 + 4200m)(t - t_1)}{M(t_2 - t)} \text{ J/kg deg C}$$

9.8 Determination of Specific Heat Capacity of a Liquid

The method of determining the specific heat capacity of a liquid is the same as given in Activity 2. The only difference is that instead of water, a liquid of unknown specific heat capacity c is taken. The solid chosen should have a known specific heat capacity c_1. It should be insoluble in the liquid and should not react with it.

We have Heat lost by the solid $= Mc_1(t_2 - t)$

Heat gained by the calorimeter and the liquid $= 400m_1(t - t_1) + mc(t - t_1)$
$= (400m_1 + mc)(t - t_1)$

According to the principle of heat exchanges:

Heat gained = heat lost

$$(400m_1 + mc)(t - t_1) = Mc_1(t_2 - t)$$

$$c = \frac{Mc_1(t_2 - t)}{(t - t_1)m} - \frac{400\,m_1}{m} \text{ J/kg deg C}$$

The only unknown quantity c can be found out by the above formula.

EXAMPLE 3. 200 g of cold water at 25.0°C is taken in a container of negligible heat capacity. A brass ball of mass 100 g is heated in boiling water to 100°C and is transferred to the water whose temperature rises to 28.5°C. Calculate the specific heat capacity of brass.

Given Mass of water $= 200$ g $= 0.2$ kg
Initial temperature $= 25.0$°C
Mass of brass ball $= 100$ g $= 0.1$ kg
Original temperature of the ball $= 100$°C
Final temperature $= 28.5$°C
Sp. heat capacity of water $= 4200$ J/kg deg C

To find Sp. heat capacity of brass $c = ?$

Solution

Heat lost by brass $= mc\Delta t$
$= 0.1c(100 - 28.5)$
$= 7.15c$ J

Heat gained by water $= 0.2 \times 4200\,(28.5 - 25)$
$= 0.2 \times 4200 \times 3.5$
$= 2940$ J

Since Heat lost = heat gained

$\therefore$ $7.15c = 2940$

or $c = \dfrac{2940}{7.15}$

$= 411.2$ J/kg deg C *Answer*

EXAMPLE 4. A copper ball weighing 3 kg after being heated in a furnace is taken out and plunged into 8 kg of water at 10°C. If the temperature of water rises to 25°C, find the temperature of the furnace. (Specific heat capacity of copper is 400 J/kgdegC, mass of container is 500 g and it is made of copper.)

Given

Mass of copper container = 0.5 kg
Mass of water = 8 kg
Initial temperature = 10°C
Final temperature = 25°C
Sp. heat capacity of copper = 400 J/kg deg C

To find

Temperature of furnace or solid = x

Solution

$$\text{Heat lost by copper ball} = mc\Delta t = 3 \times 400(x - 25) = 1200x - 30{,}000 \text{ Joules}$$

$$\begin{aligned}\text{Heat gained by container and water} &= 0.5 \times 400(25 - 10) + 8 \times 4200(25 - 10) \\ &= 15(200 + 33{,}600) \\ &= 507{,}000 \text{ Joules}\end{aligned}$$

$$\begin{aligned}\text{Since}\quad \text{Heat lost} &= \text{heat gained} \\ 1200x - 30{,}000 &= 507{,}000 \\ 1200x &= 537{,}000 \\ x &= 447.5^\circ\text{C} \quad \textit{Answer}\end{aligned}$$

9.9 Change of State

You are familiar with the fact that matter exists in three states viz., solid, liquid, or gas. The most familiar example of a substance that can exist in all the three forms is water; solid—ice, liquid—water and gas—water vapour or steam.

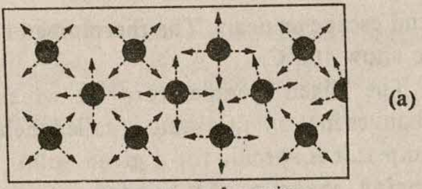
Take small pieces of ice in a beaker, fit a thermometer in it so that its bulb is surrounded by ice. Slowly heat the beaker and note the temperature. Ice begins to melt but the thermometer continues to show 0°C till the whole of the ice has melted. The temperature then begins to rise until it reaches 100°C. At this temperature water starts boiling and bubbles of vapour are seen rising to the surface where they burst and escape as steam. The thermometer continues to show 100°C.

The fixed temperature at which a solid changes into a liquid state is called **melting point.** (m.p.). It is specific for a given solid; by determining the m.p. of a substance one can check whether it is pure or not. The fixed temperature at which a liquid changes into a solid is known as its **freezing point**. For a given solid, the melting or freezing points are same. The change of state from a solid state to a liquid state is named as *fusion* and that from liquid state to solid state as *solidification.*

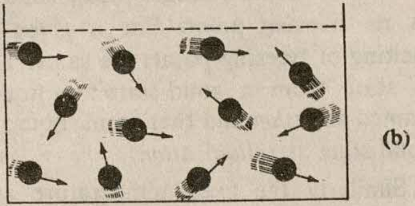
Similarly the fixed temperature at which a liquid changes into its vapour is called **boiling point** (b.p.). The change of state from a liquid to a gas is called **vapourization** and from a gas to a liquid is called **condensation.** During the change of state, whether from solid to liquid or from liquid to gas, the temperature remains constant. The heat used during the change of state cannot be detected by the rise of temperature with a thermometer, and hence is known as hidden or *latent heat.*

In a solid, molecules vibrate about their mean positions and are tightly held together by strong forces; thus heat energy possessed by the solid is just the mean kinetic energy of its molecules. When a solid is heated, the molecules vibrate more violently until a point is reached when they break away from each other and the substance melts.

Fig. 9.2 shows the difference between a solid and a liquid when both are at the same temperature—the melting point. The arrows in Fig. 9.2a, show the velocities of the molecules in the solid when they vibrate around fixed positions. The dotted arrows indicate that each molecule vibrates first in one way and then in the other. When the solid melts, the kinetic energy of the molecules and the temperature remain the same as that of the melting solid. The energy supplied is used in separating the molecules and making them free from the attractions that hold them. Thus, the energy is used in increasing the potential energy of the molecules. This is called **the latent heat of fusion.**



Arrangement and motion of molecules in a crystalline solid at the melting point.



Arrangement and motion of molecules in a liquid at the melting point.

Fig. 9.2

Remember that when a substance changes state, the potential energy of molecules changes, but their average kinetic energy remains the same; there is no change of temperature.

Molecules in a liquid have more energy and freedom but still attract each other. The hotter the liquid the faster the molecules move, so that some of the molecules have sufficient energy to break away from the bulk of the liquid. Once a molecule has broken away from the liquid, it can move around in the space above quite freely and form a gas or vapour. Work is done in separating the molecules from each other against the inter-molecular forces. The energy supplied to do this work is stored in the vapour as potential energy and is called latent heat of vaporization. When vapours condense, this potential energy is released and can be used to heat the surrounding. For this reason a burn caused by steam is always much worse than one from boiling water. Although they are at the same temperature, the steam has more energy to give up than does an equal mass of boiling water.

9.10 Heat and Internal Energy

When a substance is heated, the molecules may gain kinetic energy which increases the temperature; or they may gain potential energy which melts or evaporates the substance. Both processes increase the total or **internal energy** of the substance. *The internal energy of a substance is the sum of the kinetic and potential energies of its molecules.*

Heat is used to refer to the energy only when it is being transferred from one object to another during a temperature change or during a change of state.

Temperature and internal energy are not the same. A bucket full of water at 60°C has more internal energy than a tea cup full of water at the same temperature. **Temperature** of a substance *is a measure of the mean kinetic energy of the molecules of the substance.* It does not determine how much energy is possessed by the substance.

9.11 Specific Latent Heat of Fusion

Ice gains heat energy during melting and gives it up while freezing. 1 kg of ice at 0°C requires 336,000 J to change into water at the same temperature. This quantity is called the *specific latent heat of ice*. This process is not confined to water alone; other substances also absorb latent heat when they melt.

The **specific latent heat** *of fusion of a substance is the quantity of heat required to convert unit mass of the substance from solid to liquid state without change of temperature.* It is represented by the symbol L. The specific latent heat of fusion of ice is:

$$L = 80 \text{ cals/g} = 80{,}000 \text{ cals/kg}$$
$$= 336{,}000 \text{ J/kg}$$
$$= 336 \text{ kJ/kg}$$

The following table gives specific latent heat of fusion of some common materials.

Material	*L in kJ/kg*
Aluminium	394.8
Copper	205.8
Lead	23.1
Ice	336.0

If one knows the specific latent heat L of a substance one can calculate the amount of heat needed to change the state of m kg of it. From the definition we know that

Heat required to melt 1 kg of a substance is L.

Heat required to melt m kg of the substance will be mL

Hence $\quad Q = mL$

or Quantity of heat transferred

$= \text{mass} \times \text{specific latent heat}$

9.12 Determination of Specific Latent Heat of Fusion of Ice

Activity 3. Weigh a calorimeter along with the stirrer. Fill the calorimeter upto about half with hot water at a temperature of about 10°C above room temperature. Weigh the calorimeter along with the water and determine the mass of water taken. Dry a small piece of ice by pressing it between the folds of a blotting paper, and gently drop it in the calorimeter after noting the initial temperature. Keep on stirring the contents of the calorimeter taking care that ice is kept fully immersed in water. If need arises add another dry piece of ice, so that the final temperature is about 4-5°C below room temperature. Note the final temperature when whole of the ice has melted. Weigh the calorimeter to find the mass of ice added. Let

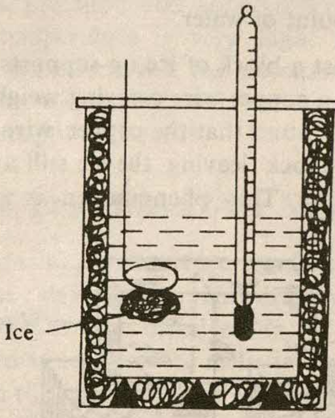


Fig. 9.3 Specific latent heat of fusion

Mass of calorimeter + stirrer

$= m_1$ kg

Specific heat capacity of copper

$= 400$ J/kg deg C

Mass of hot water taken $= m$ kg

Intital temperature of water $= t_1$°C

Final temperature of water $= t$°C

Mass of ice added $= M$ kg

Latent heat of fusion of ice $= L$ J/kg

Heat lost by water and the calorimeter

$$= m \times 4200(t_1 - t) + m_1 \times 400(t_1 - t)$$

$$= (4200m + 400m_1)(t_1 - t) \text{ Joules}$$

Heat gained by ice in melting and for rise in temperature of water formed by molten ice from 0 to t°C,

$$= ML + M \times 4200 \times (t - 0)$$

$$= ML + 4200Mt$$

According to the principle of heat exchanges:

Heat gained = heat lost

$$ML + 4200Mt = (4200m + 400m_1)(t_1 - t)$$

$$\therefore \quad L = \frac{(4200m + 400m_1)(t_1 - t)}{M} - 4200t$$

Hence specific latent heat of fusion of ice can be calculated.

9.13 Melting Point from Cooling Curve

Activity 4. Take sufficient quantity of napthalene in a boiling-test tube and hold it vertically with the help of a clamp stand. Heat it gently by a small bunsen flame until it melts. Insert a thermometer in the molten napthalene and heat further until the temperature of molten napthalene rises to about 100°C.

Remove the bunsen flame and keep on stirring the molten napthalene with the thermometer. Record the readings of the thermometer at one minute intervals. It is noticed that when napthalene begins to solidify, temperature remains constant until whole of the napthalene has solidified. After this, the temperature begins to fall again as solid napthalene cools down.

The temperature at which liquid napthalene begins to solidify is called *freezing point*. It is the same as the *melting point*.

Plot a graph between the temperature along the y-axis and the time in minutes along the x-axis. The graph thus obtained is called *cooling curve*. The flat portion of the graph repre-

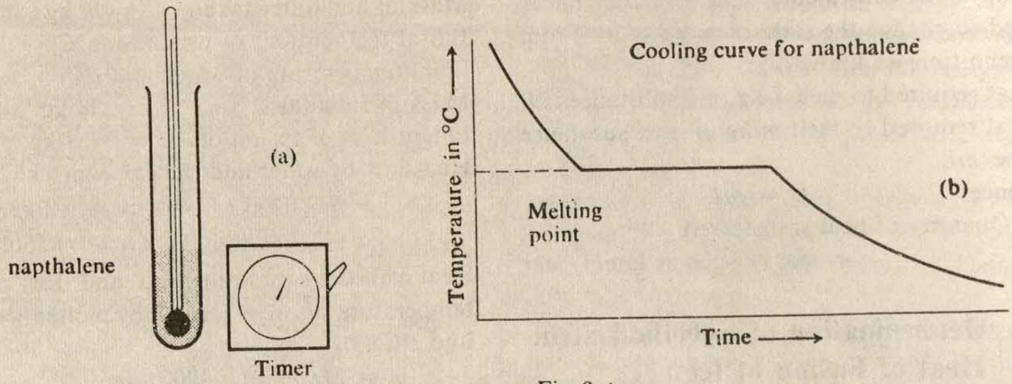


Fig. 9.4

sents the time during which liquid napthalene solidifies or solid napthalene melts. The temperature of the flat portion of the graph gives the *melting point*.

9.14 Change of Volume on Solidification

Most substances like wax contract on solidification. When molten wax contained in a beaker is allowed to solidify the surface becomes concave showing thereby that molten wax contracts on solidification (Fig. 9.5).

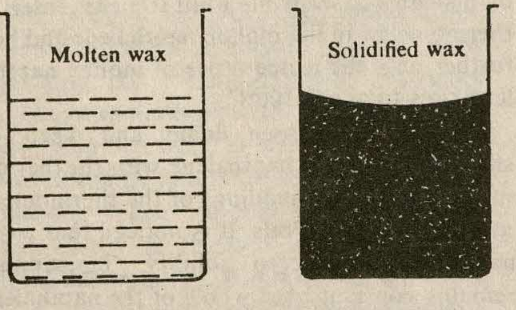


Fig. 9.5

Type metal and water expand on solidification. Because of this ice is less dense than water and floats on its surface. Water pipes are liable to burst during very cold weather because water expands on freezing. Molten type metal expands slightly on solidifying and thus takes up a very sharp impression of the mould.

9.15 Effect of Pressure on Melting Point (Regelation)

You know that water expands on freezing. When pressure is exerted on water being cooled, increase of pressure decreases the volume and prevents water from expanding and, therefore, from freezing. In other words, pressure lowers the freezing point of water.

Activity 5. Rest a block of ice on supports and hang over it a copper wire carrying weights at each end. It is found that the copper wire cuts through the block leaving the ice still a solid block (Fig. 9.6). This phenomenon is called *regelation*.

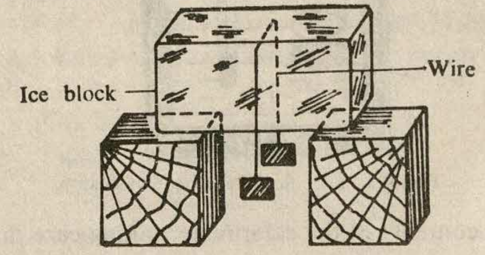


Fig. 9.6 Regelation

The pressure exerted by the wire lowers the melting point of ice under it, which consequently melts. Molten water comes above the wire and as it is no more under pressure, it freezes, being at a temperature less than 0°C. In doing so it gives out latent heat which is conducted down through the wire to help further melting of ice under the wire.

When some powdered ice is squeezed together, the melting point is slightly lowered because of the increased pressure and some melting takes place. When the pressure is released, the water promptly freezes and the snow or powdered ice is packed into a ball.

A skater exerts pressure on the ice below the skates. The ice temporarily melts and freezes immediately after the skater has moved away. Thus the skater actually slides along on a thin film of water. If the skates are sharp, the pressure is more. This lowers the m.p. still more and the skates dig deep into the ice. Because of this, the skates are less apt to slip sideways. In severe winter, ice may become too cold. The pressure exerted by the skates may then not be sufficient to lower the melting point below the temperature of ice. The ice, then, does not melt and skating becomes difficult.

Most of the materials contract on solidification. Increase of pressure in their case raises the m.p. Rocks beneath the Earth are under very high pressure, and so do not melt even when the temperature is very high. If rock layers above are removed, the pressure decreases. The rocks below may then melt and cause a volcanic eruption to occur.

9.16 Impurities Lower Melting Point

The melting point of ice or freezing point of water can be considerably lowered when certain substances are dissolved in it. When salt is added to ice some ice melts taking latent heat from the mixture whose temperature falls below 0°C. Further, the salt dissolves in water formed and takes the heat of dissolution from the mixture whose temperature is decreased further. Mixture of salt with ice is called freezing mixture and is used in home ice-cream freezers.

The same principle is involved when salt is sprinkled on snowy streets to melt away the snow. The addition of salt lowers the freezing point below the temperature of snow which consequently melts. The use of calcium chloride is preferred because it is cheaper and is more effective.

9.17 Latent Heat of Vapourization

Boiling water needs heat to change into vapour and steam gives out heat to condense into water at the same temperature. *The specific latent heat of vapourization of a substance is the quantity of heat required to change unit mass of the substance from liquid to vapour state without change of temperature.* It is denoted by a symbol L and its SI unit is Joule per kilogram (J/kg) However, to avoid the use of large numbers kJ/kg may be used instead.

Specific latent heat of vapourization of water is 540 cals/g, 540,000 cals/kg or 2,260,000 J/kg. It is convenient to write it as 2260 kJ/kg or 2.26 MJ/kg.

EXAMPLE 5. Calculate the amount of heat required to completely change 5 g of ice at $-10°C$ into steam. (c of ice $= 2100$ J/kg; L of fusion of ice $= 336$ kJ/kg; c of water $= 4200$ J/kg and L of steam $= 226$ MJ/kg.)

Solution

(i) Heat required to raise the temperature of ice from $-10°C$ to $0°C$

$$= mc\Delta t$$
$$= 0.005 \times 2100 \times [0 - (-10)]$$
$$= 0.005 \times 2100 \times 10$$
$$= 105 \text{ J}$$

(ii) Heat required to melt ice

$$= mL = 0.005 \times 336{,}000$$
$$= 1680 \text{ J}$$

(iii) Heat required to raise the temp. of water, formed from ice, from 0 to 100°C.

$$= mc\Delta t = 0.005 \times 4200 \times 100$$
$$= 2100 \text{ J}$$

(iv) Heat required to change water to steam

$$= mL = 0.005 \times 2{,}260{,}000$$
$$= 11{,}300 \text{ J}$$

Total heat required

$$= 105 + 1680 + 2100 + 11{,}300$$
$$= 15{,}185 \text{ J}$$ *Answer*

EXAMPLE 6. 200 g of hot copper is dropped on a block of ice at 0°C. As a result 200 g of ice melts. What was the temperature of copper when it was dropped (c of copper $= 400$ J/kg; L of fusion of ice $= 336{,}000$ J/kg).

Solution

Let the temperature of copper be θ; then

Heat lost by copper

$$= mc\Delta t = 0.2 \times 400 \times \theta$$
$$= 80\theta \text{ Joules}$$

Heat gained by ice in melting

$$mL = 0.2 \times 336{,}000$$
$$= 67{,}200 \text{ Joules}$$

Since Heat lost $=$ heat gained

$$\therefore \quad 80\theta = 67{,}200$$
$$\theta = 840°\text{C}$$

Example 7. 300 g molten lead at its melting point of 327°C is dropped into 400 g of water at 15°C in an aluminium container of mass 30 g. The final temperature is 26°C. Find the specific latent heat of fusion of lead. (c of lead $= 130$ J/kg deg C; c of aluminium $= 910$ J/kg deg C; c of water $= 4200$ J/kg deg C.)

Solution

Heat lost by lead in solidifying

$$= mL = 0.3L \text{ Joules}$$

Heat lost by solid lead in cooling to 26°C

$$= mc\Delta t = 0.3 \times 130 \times 301$$
$$= 11{,}739 \text{ Joules}$$

Total heat lost

$$= 0.3L + 11{,}739 \text{ Joules}$$

Heat gained by water

$$= mc\Delta t = 0.4 \times 4200 \times 11$$
$$= 18{,}480 \text{ Joules}$$

Heat gained by calorimeter

$$= mc\Delta t = 0.03 \times 130 \times 11$$
$$= 43 \text{ J}$$

Total heat gained

$$= 18{,}480 + 43 = 18{,}523 \text{ J}$$

Since Heat lost $=$ heat gained

$$\therefore \quad 0.3L + 11{,}739 = 18{,}523$$

$$L = \frac{6784}{0.3}$$
$$= 22{,}613 \text{ J/kg}$$

Answer

9.18 Evaporation and Boiling

A wet cloth spread in the Sun dries up due to the evaporation of water from its surface. *The change of state from a liquid to a gas at any temperature is called* **evaporation** *and the one at a fixed temperature is called* **boiling**.

Evaporation takes place from the surface of the liquid while boiling takes place in the entire mass of the liquid. Evaporation is a slow and silent process and the temperature does not remain constant during it. Boiling is a quick and violent process and the temperature remains constant as long as the entire liquid has not boiled off.

The rate of evaporation is fast if the surface area is more, wind is blowing, humidity is low, and the temperature is high. These factors do not affect boiling.

9.19 Cooling Caused During Evaporation

Liquids having low boiling point evaporate easily at ordinary temperatures and are called *volatile liquids*, such as alcohol, petrol and ether. Pour some methylated spirit on the palm of your hand. It evaporates rapidly and the hand feels cold. We can say that cooling is caused during evaporation. This is because the latent heat of evaporation is partly taken from the hand and the rest from the atmosphere, hence the hand feels cold as it has lost some heat.

Activity 6. Pour some water on a flat piece of wood and place on it a beaker containing some ether. Blow through the ether to increase its rate of evaporation. Latent heat of evaporation

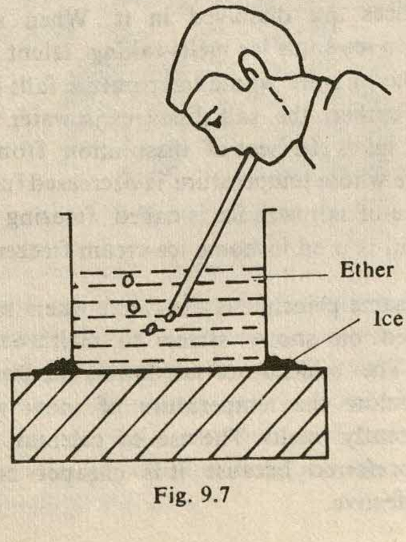


Fig. 9.7

is partly taken from the ether itself and partly from the surroundings. Soon the temperature of ether falls below 0°C and the water below the beaker eventually freezes (Fig. 9.7).

According to the kinetic theory, all the molecules of a liquid do not vibrate with the same speed. Faster molecules possess greater kinetic energy and slower ones are less energetic. Mean kinetic energy of the molecules of the liquid gives its temperature. Fast moving energetic molecules are likely to escape from the surface of the liquid and become free as vapour. This process is called evaporation. The mean kinetic energy of the molecules left behind becomes less, hence the temperature falls. This explains why cooling is caused during evaporation.

QUESTIONS

1. At the time of Rumford, what was the general belief among scientists about the nature of heat. What conclusion did Rumford draw about the nature of heat?

2. Explain why a drill becomes hot during use?

3. Explain the following :

(a) when the brakes of a moving car are applied for appreciable time, they get hot;

(b) when the tyre of a car is pumped, the pump gets warm.

4. Define calorie and kilocalorie and give the relations between these and the joule.

5. The specific heat capacity of aluminium is 910 joules/kg deg C. What do you mean by this? The specific heat capacity of water is very high. In which ways is this put to use?

6. Distinguish between heat capacity and specific heat capacity of a substance. Give the units in which they are measured.

7. How many joules of heat are given out when a piece of iron of mass 100 g and specific heat capacity 460 J/kg deg C cools from 80°C to 20°C?

8. What is the final temperature of a mixture of 100g of water at 70°C and 200g of cold water at 10°C? (Neglect the heat absorbed by the container.)

9. Describe a method to find the specific heat capacity of a solid. Give necessary calculations and state the precautions which you would observe, with reasons.

10. The temperature of 500g of a certain metal is raised to 100°C and is then placed in 200g of water at 15°C. If the final steady temperature is 21°C, calculate the specific heat capacity of the metal.

11. A piece of copper of mass 40 g at 200°C is placed in a copper calorimeter of mass 60 g containing 50g of water at 10°C. Ignoring the heat losses, what will be the final steady temperature after stirring? (Specific heat capacity of copper = 400 J/kg deg C.)

12. How can you explain on the basis of the kinetic theory the change of state from (a) a liquid to a gas; (b) a solid to a liquid.

13. Why are pieces of ice at 0°C, added to a drink at room temperature, more effective in cooling the drink than an equal mass of water at 0°C?

14. What do you mean by the internal energy of an object? Which possesses greater internal energy, a gram of water at boiling point or a gram of steam at the same temperature? Why?

15. If the molecules of two objects have the same average kinetic energy, are these two objects at the same temperature? Do they have the same internal energy?

16. What do you mean by specific latent heat of fusion of a substance? In which unit or units is it measured? Describe a method to determine the latent heat of fusion of ice. Give necessary precautions and calculations.

17. Why does a wet cloth on a container cool the water inside? Which process requires more energy, the evaporation of 1g of water or the melting of 1g of ice?

18. An aluminium container weighing 24 g contains 245 g of water at 27.0°C. 34 g of ice are dropped into the calorimeter and the contents stirred until the mixture reaches a final temperature of 14.0°C. Calculate the specific latent heat of fusion of ice, given that *c* of aluminium = 880 J/kg deg C.

19. What do you mean by melting point of a solid? Describe the cooling curve method of finding the m.p. of a solid. Illustrate your answer with diagrams.

20. The temperature of napthalene contained in a test tube is recorded every half minute as it is heated from 60 to 90°C. Show the nature of the graph otbained on plotting temperature against time and explain its shape, given that m.p. of napthalene is 80°C.

21. How does increased pressure affect the m.p. of ice? Describe an experiment to illustrate this.

22. Speed skates have sharper blades than the usual skates. Why is this so?

23. The melting point of ocean water is — 2.5°C and that of tap water is 0°C. Explain why? Compare the boiling point of ocean water with that of distilled water. Explain the difference.

24. The liquid part of blood is water with various substances dissolved in it. What would you expect its freezing temperature to be?

25. The specific latent heat of vapourization of ethyl alcohol is 860 J/kg. What do you mean by this? Calculate the amount of heat required to boil off 100 g ethyl alcohol at its boiling point of 78°C.

26. Calculate the heat required to convert 5 g of ice at — 6°C to steam at 100°C. (*c* of ice is 2100 J/kgdegC; *L* of fusion of ice is 3,36,000 J/kg and *L* of steam is 22,60,000 J/kg.)

27. The temperature of a piece of copper of mass 250 g is raised to 100°C and is then transferred to a well-lagged aluminium can of mass 10 g containing 120 g of methylated spirit at 10.0°C. Calculate the final steady temperature when *c* for copper is 400 J/kgdegC; *c* of aluminium is 900 J/kgdegC and of spirit is 2400 J/kg deg C. Neglect the heat losses due to evaporation.

28. Calculate the quantity of heat required to completely melt 100 g of lead initially at 27°C. (For lead melting point = 327°C; mean specific heat capacity = 140 J/kgdegC; specific latent heat of fusion = 270 kJ/kg.)

If the heat is supplied to lead at the rate of 30 J/s find :

(a) time taken to bring the lead to its m.p.

(b) additional time required to melt it.

29. A 24.0 g aluminium calorimeter contains 220.0 g of water at 14.0°C. Steam at a temperature of 99.0°C is bubbled into the calorimeter until the contents reach a temperature of 27.0°C. A second weighing of the calorimeter shows that it now contains 225.0 g of water. What is the latent heat of vapourization of water? (*c* of aluminium = 880 J/kg deg C.)

30. Distinguish between evaporation and boiling. Name four factors which accelerate the rate of evaporation of a liquid.

31. Describe briefly two methods by which a liquid may be made to evaporate more quickly (other than direct heating). Give reasons.

32. Explain on the basis of kinetic theory of matter that cooling is caused during evaportion.

10

Rectilinear Propagation of Light

If we were to shut ourselves in a completely dark room, we would realize what the world would be without light. A blind man knows what a great blessing the eyes are. The moment we switch on the light our invisible surroundings become visible. **Light** is the energy which enables a person to see objects around him with the help of eyes.

A lamp gives off its own light; tables, chairs, walls, mirrors and glass panes do not emit their own light but become visible when light from a lamp or any other luminous object falls on them. *An object which emits its own light is called a* **luminous object**. *An object which does not give off its own light, but becomes visible when light from a luminous object falls on it is called a* **non-luminous object.** To become visible a non-luminous object must *reflect* the light incident on it to our eyes. The word reflect in the general sense means to 'throw back'. The Sun and stars are luminous but the Moon and the planets are non-luminous. The moment the light from the Sun is blocked off to reach the Moon at the time of a total lunar eclipse, it becomes dark.

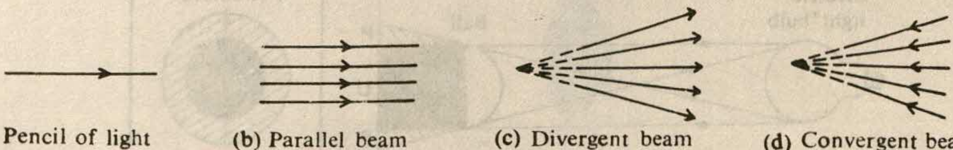
It will appear strange to you to know that light itself is invisible but when it falls upon objects, they become visible. Even during the daytime, to an astronaut the space outside his vehicle appears to be pitch dark. We often say that we 'see' light; this is a wrong statement. We actually see dust particles and moisture which reflect light falling on them to our eyes.

10.1 Light Travels in Straight Lines

Spot-light beams and sharp edges of shadows suggest that light travels in straight lines. All our daily experiences with light are based upon the assumption that light travels in straight lines. For example, to illuminate an object in the dark, you point a lighted torch directly at it.

The path along which light travels is known as a **ray of light**. It is represented in diagrams by a straight line with an arrow giving the direction of propagation of light.

Every point on an object emits thousands of rays of light in all directions. Only a small portion of these fall on the eye. *A collection of rays of light is called a* **beam** *of light.* A narrow beam is termed a *pencil* of light. A beam of light could be parallel, divergent or convergent. Rays of light reaching us from a very far off



(a) Pencil of light (b) Parallel beam (c) Divergent beam (d) Convergent beam

Fig. 10.1

object such as the Sun, are almost parallel to each other. A divergent beam is one in which rays spread out. In a convergent beam, rays of light tend to come together and would eventually meet at a point.

10.2 Transmission of Light

Hold your palm in the path of light from a source to your eyes. The light is obstructed and you cannot see the source now. An object which does not allow light to pass through it is called an **opaque** object. Wood, stone, metal and your palm are opaque objects. A **transparent** substance like glass, air and a thin layer of water allows most of the light that falls on it to pass through, and we can, therefore, see clearly through it.

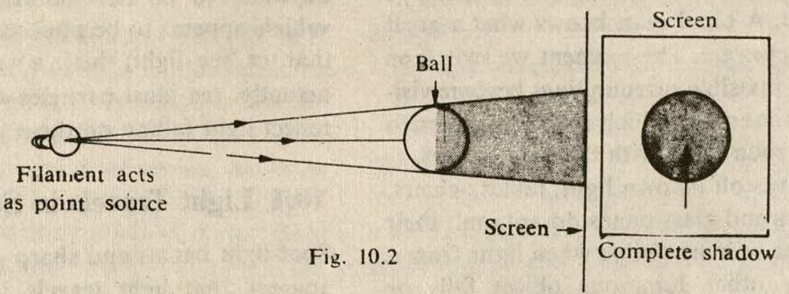


Fig. 10.2

There are some substances like tissue paper, waxed paper and frosted glass which allow only a portion of the light to pass through. We cannot, however, see through them. Such substances are called **translucent**. Frosted window glasses are translucent. Light from outside can enter through them, but people cannot see in or out.

In air, light travels with a speed of about $300{,}000\ \text{km s}^{-1}$ or 186,000 miles per second. The distance around the Earth at the Equator is about 40,000 km. This means that it takes approximately 1/5th of a second for light to go round the Earth, which is the approximate time you take to blink your eyes! Light takes about 8½ minutes to travel from the Sun to the Earth and several years to travel from the stars to the Earth. Its speed in glass and water is slower, about 225,000 km/s in water and 200,000 km/s in glass. You will read about this later.

10.3 Shadows

A shadow is formed on a screen when an opaque object placed in between a source and the screen stops light from reaching it. The type of the shadow obtained depends on the size and position of the light source and screen.

Activity 1. In a darkened room hold an opaque ball between a point source of light and the screen as shown in Fig. 10.2. A completely dark shadow with sharp edges appears on the screen. This type of shadow is called *umbra*.

Repeat the experiment with a large 'frosted' or 'pearl' electric lamp. Two round shadows appear. In the middle there is a completely dark shadow (umbra) and around it is a partly dark shadow called *penumbra*.

Move the opaque ball towards the lamp. How does the shadow alter?

When an opaque object is placed in between a source of light and a screen, the area of the screen from which the light is cut off fully or

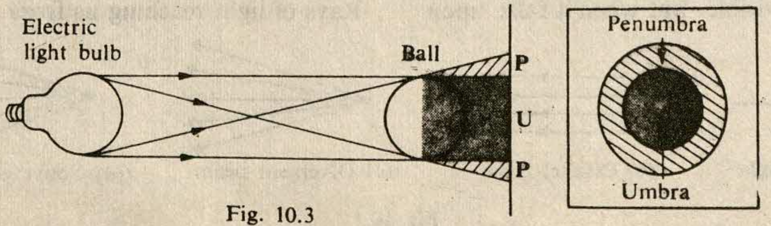


Fig. 10.3

partly is called a **shadow**. *If the light is blocked off fully, the shadow is completely dark and is called* **umbra**. *On the portion of the screen from which the light is cut off partially, the shadow is partly dark and is called* **penumbra**.

The formation of shadows is based upon rectilinear propagation of light.

10.4 Eclipses

The Sun is about four hundred times larger than the Moon, but it is also about four hundred times farther away from us. For this reason, the Sun and the Moon appear to be of the same size in the sky.

The Sun is a luminous object while the Earth and the Moon are opaque and non-luminous. The Earth revolves around the Sun once in a year and the Moon revolves around the Earth once in about 28 days. It happens sometimes that all three come in one straight line and either the shadow of the moon falls on the Earth or that of the Earth falls on the Moon; thus eclipses are caused. Eclipses are shadows formed on cosmic scale and are based upon the fact that light travels in straight lines.

Solar Eclipse

The solar eclipse is caused when the shadow of the Moon falls on the Earth on a particular new Moon day (Fig. 10.4). At places on the Earth which fall in the umbra, like *a* in Fig. 10.4, the Sun is completely blocked by the Moon and total eclipse of the Sun is observed from there. Places which fall in the penumbra experience a partial eclipse as in the case of *b* and *c*. It is necessary to remember that, during an eclipse, the Sun should not be viewed directly

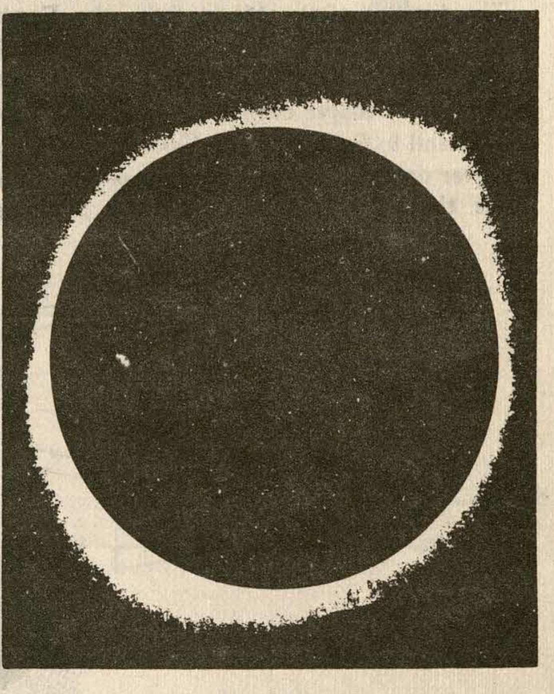
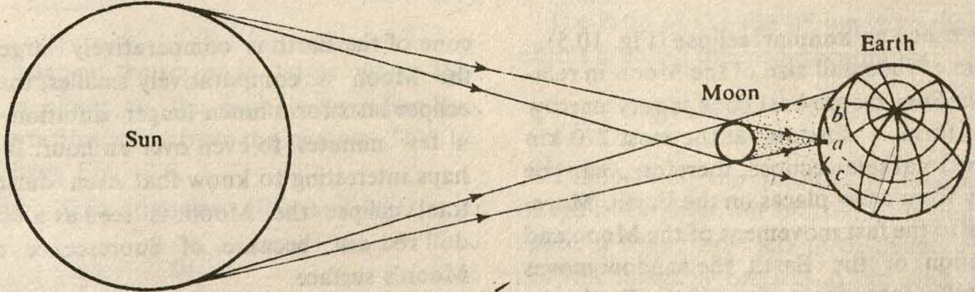
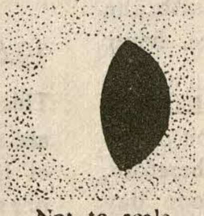


Fig. 10.4 (b) Total Solar eclipse





Not to scale

Fig. 10.4 (a) Partial Eclipse

with the naked eye. It should be viewed only through a smoked screen or an exposed film.

A study of the Sun's corona can best be made from positions where total solar eclipse occurs and the disc of the Sun is fully covered by the Moon's disc. The corona, which is at a relatively lower temperature, now becomes visible as shown in Fig. 10.4b.

The distance of the Moon from the Earth varies from time to time because the orbit of the Moon around the Earth is elliptical. On certain solar eclipse days the umbral cone may not extend to the Earth; the Moon is then seen to cover only the middle portion of the Sun while the outer bright ring is visible. Such an eclipse is called an annular eclipse (Fig. 10.5).

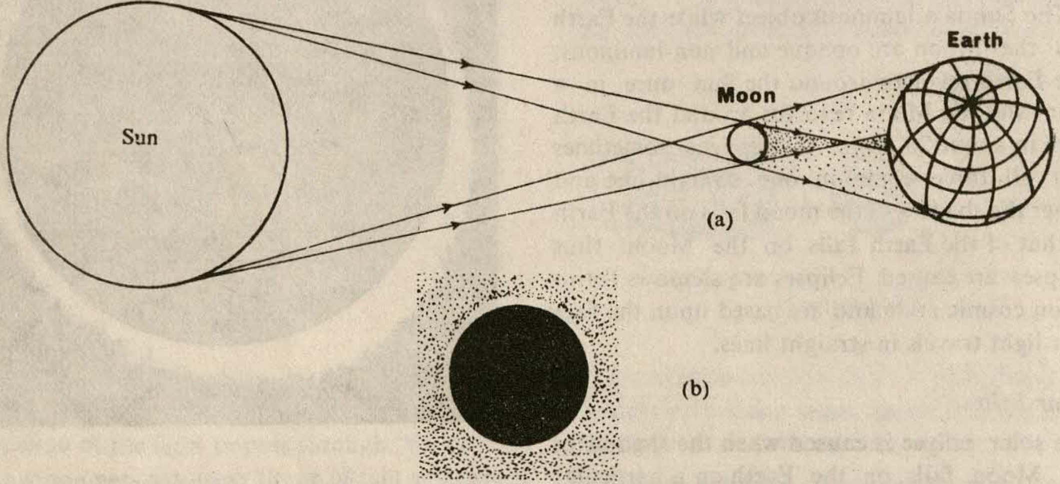


Fig. 10.5 Annular Eclipse

Because of the small size of the Moon in relation to the Sun, the umbral cone is very narrow and can form a shadow at the most 270 km wide. The total solar eclipse, therefore, can be seen only from a few places on the Earth. Moreover, due to the fast movement of the Moon and the rotation of the Earth, the shadow moves away rapidly from the surface of the Earth; the total solar eclipse at any place, therefore, never lasts more than seven minutes.

The orbit of the Moon around the Earth is inclined at an angle of 5° to the orbit of the Earth around the Sun. A solar eclipse, therefore, does not take place on every new moon day when the Moon is in the middle with the Earth and the Sun on either side as they are not in the same plane. Only 2 to 5 solar eclipses take place every year out of the 12 or 13 new moon days.

Lunar Eclipse

Eclipse of the Moon occurs on a particular full Moon day when the Earth comes between the Sun and the Moon and they are in one straight line. In this condition the shadow of the earth falls on the Moon. The eclipse is partial when the moon is partly in the umbral shade and total when the whole disc of the moon is in the umbra (Fig. 10.6).

The lunar eclipse is seen from the entire half of the Earth facing the moon. Since the umbral cone of the Earth is comparatively larger and the Moon is comparatively smaller, the lunar eclipse lasts for a much longer duration—from a few minutes to even over an hour. It is perhaps interesting to know that even during the total eclipse the Moon is seen as a coppery, dull red disc because of fluorescence on the Moon's surface.

10.5 Pinhole Camera

This is the simplest type of camera and its action is based upon the rectilinear propagation of light. It consists of a box with a pinhole on one side and a translucent screen on the opposite

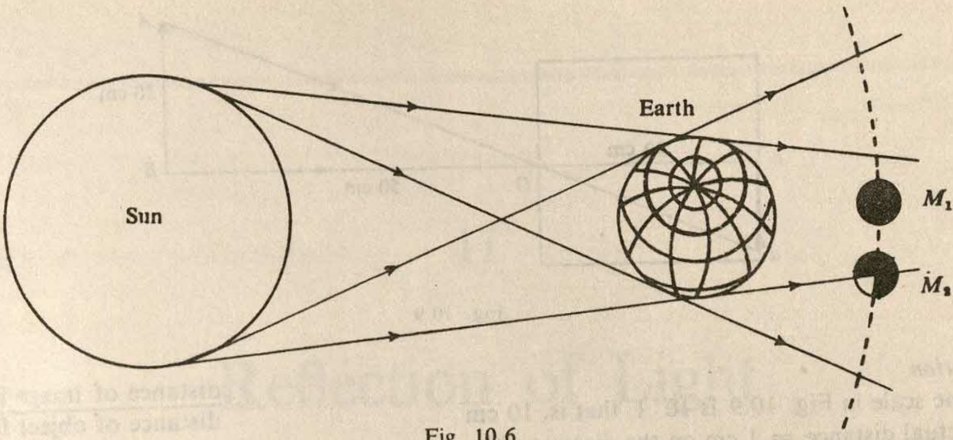


Fig. 10.6

side. The pinhole side is pointed at the object to be viewed. One ray of light from each point on the object passes through the pinhole to form a likeness or image of it on the screen. The image is formed on the screen and is inverted (Fig. 10.7).

The size of the image depends upon the distance of the object from the pinhole, and the distance of the pinhole from the screen.

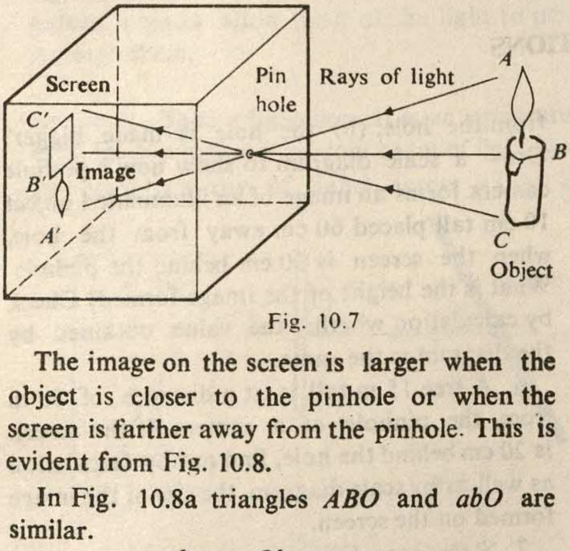


Fig. 10.7

The image on the screen is larger when the object is closer to the pinhole or when the screen is farther away from the pinhole. This is evident from Fig. 10.8.

In Fig. 10.8a triangles *ABO* and *abO* are similar.

$$\text{Therefore } \frac{ab}{AB} = \frac{Ob}{OB}$$

$$\text{or} \quad \frac{\text{Size of image}}{\text{Size of object}} = \frac{\text{distance of image from hole}}{\text{distance of object from hole}}$$

$$\text{or} \quad \frac{I}{O} = \frac{v}{u}$$

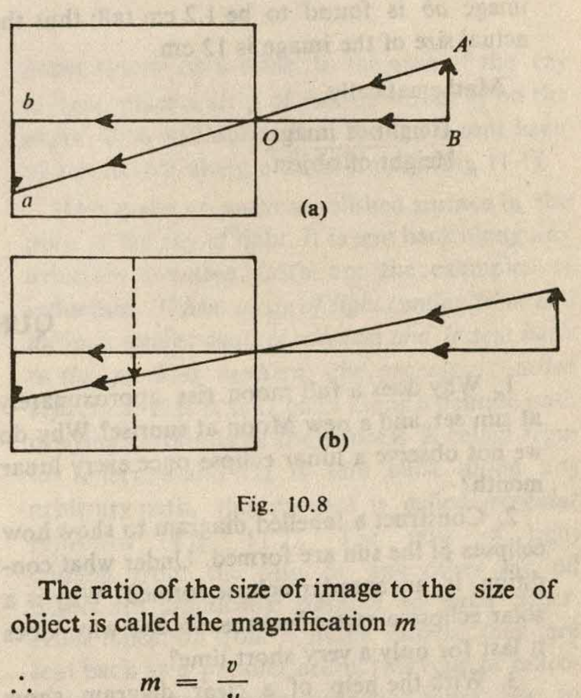


Fig. 10.8

The ratio of the size of image to the size of object is called the magnification *m*

$$\therefore \quad m = \frac{v}{u}$$

If the size of the pinhole is increased, the image is brighter but blurred. It is brighter because a bigger hole lets through more light, so that the image is bright. A big hole can be assumed to be made of many pinholes, each pinhole making its own image. These images overlap and hence the final image is blurred.

EXAMPLE 1. A 20 cm tall object is placed 50 cm away in front of a pinhole camera which is 30 cm wide. What will be the size of the image?

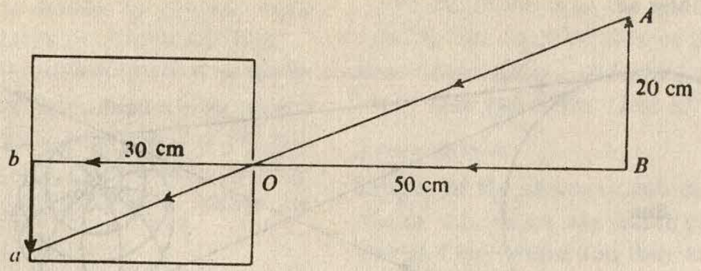


Fig. 10.9

Solution

The scale in Fig. 10.9 is 10 : 1, that is, 10 cm of actual distance = 1 cm on the diagram. The image *ab* is found to be 1.2 cm tall; thus the actual size of the image is 12 cm.

Mathematically,

$$\frac{\text{Height of image}}{\text{Height of object}} = \frac{\text{distance of image from hole}}{\text{distance of object from hole}}$$

$$\therefore \quad \frac{\text{Height of image}}{20 \text{ cm}} = \frac{30 \text{ cm}}{50 \text{ cm}}$$

$$\text{Hence, Height of image} = \frac{30 \text{ cm}}{50 \text{ cm}} \times 20 \text{ cm}$$

$$= 12 \text{ cm}$$

Answer

QUESTIONS

1. Why does a full moon rise approximately at sun set, and a new Moon at sunrise? Why do we not observe a lunar eclipse once every lunar month?

2. Construct a labelled diagram to show how eclipses of the sun are formed. Under what condition is an annular eclipse formed? Why is a solar eclipse a rare phenomenon and why does it last for only a very short time?

3. With the help of a clear diagram show how an eclipse of the Moon takes place. Why should a lunar eclipse take place only on a full moon night?

4. Why are lunar eclipses more common than solar eclipses? Why is a lunar eclipse observed over a larger area and for a larger time than a solar eclipse?

5. How does the image in a pinhole camera change if (a) the screen is moved further away from the hole; (b) the hole is made bigger? Draw a scale diagram to show how a pinhole camera forms an image of an illuminated object 10 cm tall placed 60 cm away from the hole, when the screen is 30 cm behind the pinhole What is the height of the image formed? Check by calculation whether the value obtained by the diagram is the same.

6. A tree 15 m tall is at a distance of 30 m from the pinhole of a camera. If the screen is 20 cm behind the hole, find out by calculation as well as by scale diagram, the size of the image formed on the screen.

7. State three differences between an image formed in a pinhole camera and a shadow. Draw a diagram to show the formation of umbra and penumbra of a hockey ball on a wall when held in front of a glowing milky glass bulb.

11

Reflection of Light

As we saw in the last chapter an object is either transparent, translucent or opaque. When light falls on it, one or more of the following may happen: (a) it may pass through the object; (b) it may get absorbed; (c) it may be thrown back. Polished surfaces send back most of the light while dull surfaces mostly absorb it. Transparent objects allow most of the light to pass through them.

Activity 1. Take a light box. It is an apparatus used for producing a narrow beam of light (you may call it a ray of light) across a sheet of paper spread on a table. In the path of the ray of light, place a strip of mirror vertically on the paper. You will notice that the ray is sent back by the mirror along a definite path (Fig.11.1).

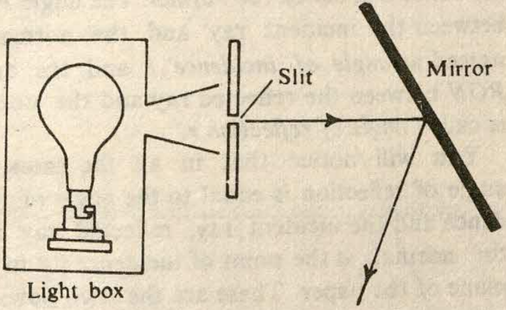


Fig. 11.1

Now place an uneven polished surface in the path of the ray of light. It is sent back along any arbitrary direction. Both are the examples of **reflection**. *When a ray of light coming from one medium strikes another medium and is sent back to the previous medium, the process is called reflection.* If it is sent back along a definite path obeying certain laws the process is called *regular reflection* and if it is sent back along any arbitrary path, the process is called *irregular reflection* (Fig. 11.2). The rays of light coming from the Sun or any other far off object are practically parallel to each other. After reflection from a plane mirror they are sent back as a parallel beam; this type of reflection is regular. Regular reflection gives rise to glares and the formation of images as well.

When a parallel beam is directed on an uneven polished surface, you will notice that the

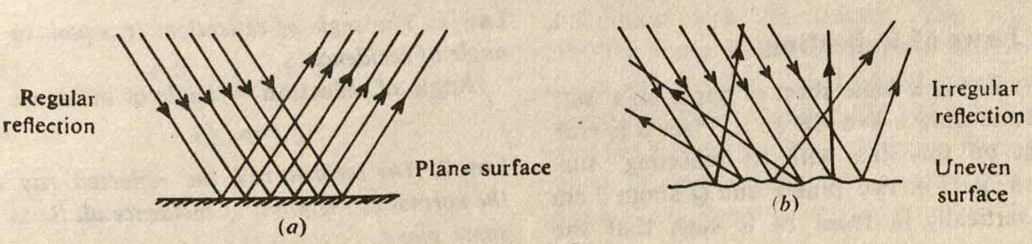


Fig. 11.2

incident light is scattered in all directions (Fig. 11.2b). This is the case of irregular or diffused reflection and enables us to see opaque objects from all directions.

The fraction of incident light reflected by an object depends upon (a) the kind of material of which it is made; (b) the smoothness of the surface; and (c) the angle at which the light strikes its surface.

A smooth polished surface reflects most of the incident light while a black surface absorbs most of it. Transparent objects like air and clean window panes allow most of the light to pass through them and do not reflect much light to be seen clearly.

Reflecting surfaces vary in the extent to which the reflected rays are scattered. A plane polished surface scatters negligible amount of light and reflects most of it while a rough uneven surface scatters most of the light and reflects very little (see Fig. 11.3 a and b).

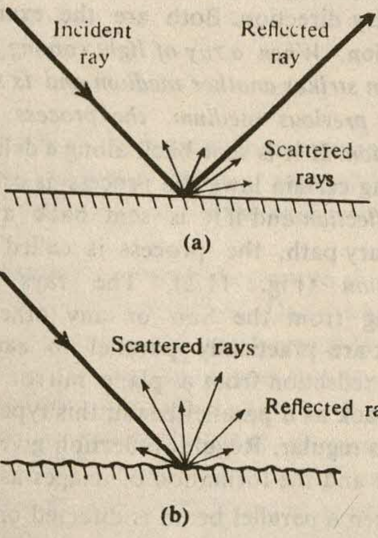


Fig. 11.3

11.1 Laws of Reflection

Activity 2. Fix a white sheet of paper on a soft board and draw a line AB on it. Place a mirror upright on this line with its reflecting surface on it. Fix two pins P and Q about 5 cm apart vertically in front of it such that the line joining them meets the mirror at an angle. Now place your eye on the other side such that the images of P and Q are behind each other. Fix two more pins R and S such that they are in one straight line with the images of P and Q. They give the direction of the reflected ray.

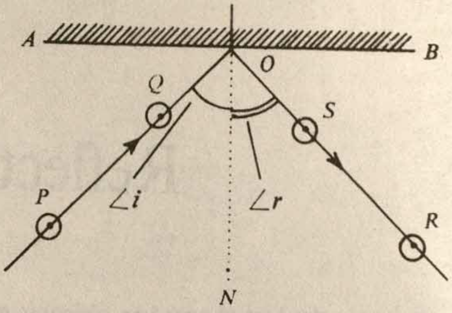


Fig. 11.4

Now remove the mirror and join PQ and RS to meet the line AB at O. Draw a perpendicular NO to the line AB at O. Meausre the angles PON and RON. Repeat the experiment for different inclinations of PQ.

The line PQO along which the light is incident on the mirror is called the *incident ray* and the line OSR along which the ray is sent back after reflection is named as the *reflected ray*. The perpendicular NO on the mirror at the point of incidence O is called the *normal*. The angle PON between the incident ray and the normal is named as *angle of incidence* i and the angle RON between the reflected ray and the normal is called *angle of reflection* r.

You will notice that in all the cases, the angle of reflection is equal to the angle of incidence and the incident ray, reflected ray and the normal at the point of incidence lie in the plane of the paper. These are the two laws of reflection.

Law 1. *The angle of reflection is equal to the angle of incidence.*

Angle of reflection = angle of incidence

$$\angle r = \angle i$$

Law 2. *The incident ray, the reflected ray and the normal at the point of incidence all lie in the same plane.*

11.2 Image Formed by a Plane Mirror

When you look into a plane mirror you are looking at your own image in it. When you fix a pin in front of a plane mirror you can easily see its image from different positions of the eye. Even when you change the position of eyes—forwards, sideways or backwards—the image position appears to remain fixed. Where is this image?

Activity 3. The image formed by a plane mirror can also be located with the help of pins. Fix a white sheet of paper on a soft board and place a plane mirror vertically along a line *MN*. Fix a pin vertically at a point *S* which serves as an object. Fix another pin *A* so that *SA* becomes an incident ray. Obtain its reflected ray *CD* by fixing two pins. Similarly take another incident ray *SB* and trace its reflected ray *EF*. Now remove the mirror and the pins. Produce both the reflected rays *CD* and *EF* backwards (Fig. 11.5) to obtain the point of intersection *I*, which is the image of *S*. Join *IS* and mark *O*, the point of intersection of *IS* and *MN*. Measure the distance *IO* and *OS*, and $\angle IOM$. You will find that $\angle IOM$ is a right angle, within the limits of experimental error, and $OI = OS$. Repeated experiments show that the perpendicular distances of the image and object from the mirror are equal. For example if you stand 1 metre in front of a plane mirror, your image will be 1 metre behind the mirror. Thus, the image formed by a plane mirror is as much behind the mirror as the object is in front of it.

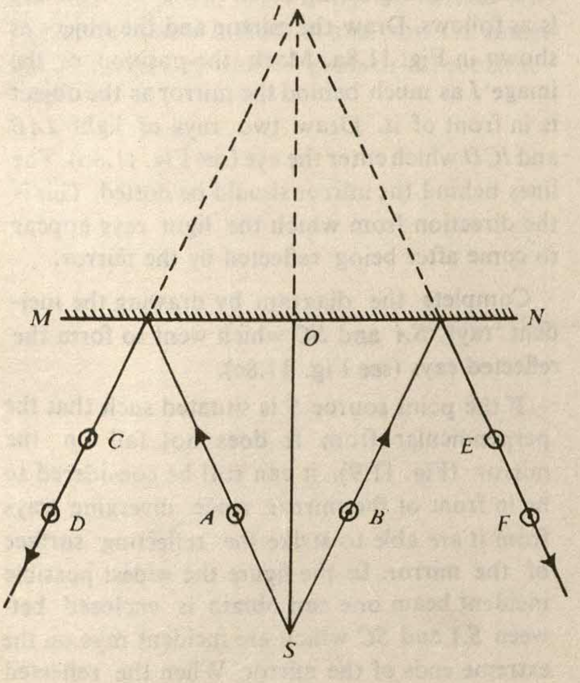


Fig. 11.5

11.3 Virtual Images

The image formed by a plane mirror appears very much like the object and gives an impression of sending out light which we receive. Actually, this image has no real existence and the light comes directly from the object after reflection at the mirror surface. No light reaches the image and it cannot be taken on a screen. Such an image is called a **virtual image.** In contrast, the image formed in a pinhole camera is real; it is taken on a screen, light actually reaches there, and it scatters the light in all directions which is directly received by our eyes.

Activity 4. Hold a pencil in front of a plane mirror and you will notice that its image is as big as the pencil itself. Try it with a book, your fingers or any other object. In all cases you will find that the size of the image by a plane mirror is the same as the size of the object.

You will also notice that the image seen in a plane mirror is upright, whereas the image in a pinhole camera is inverted.

However, the image in a plane mirror does get inverted in a peculiar way. Stand in front of a plane mirror and raise your right hand to shake hand with your image. You will find that the image raises its left hand in response. If you write with your right hand, your image appears to be left handed (Fig. 11.6). If some words on a paper are held close to a mirror, the image of the words appears reversed from side to side. This type of inversion is called **lateral inversion**. It is easy to see how this happens if

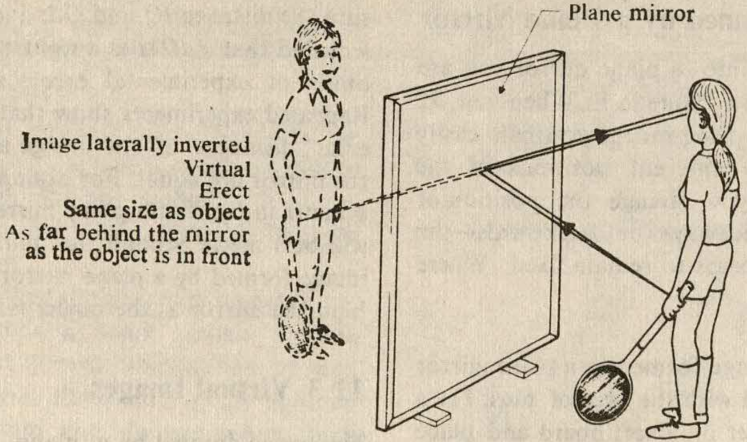


Fig. 11.6

you locate the corresponding image of each point of the object which is as much behind the mirror as the object is in front.

11.4 Image of a Point Object

A diagram showing how the image of a point object is formed by a plane mirror, and the position of our eye to view such an image, requires careful construction. The following methods are suggested.

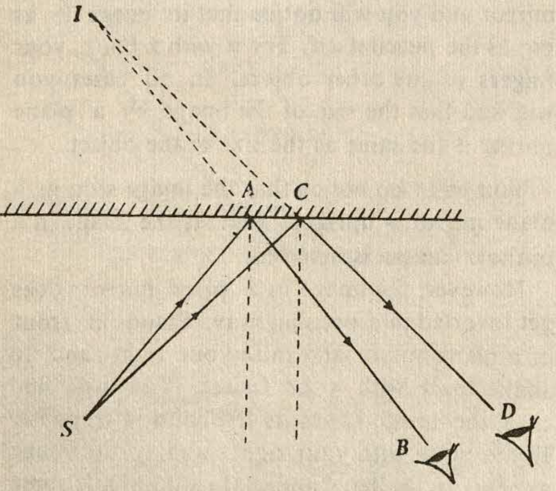


Fig. 11.7

Activity 5. In order to construct the image of a point object *S* (Fig. 11.7), take two rays from *S* incident on the mirror. Draw normals to the mirror at the points of incidence *A* and *C*. Find the angles of incidence and hence draw the reflected rays *AB* and *CD*. The two reflected rays will form a diverging beam and, when produced backwards, they intersect at *I* and so will appear to come from the virtual image *I*.

A simpler method which makes measurement of angles and drawing of normals unnecessary is as follows. Draw the mirror and the object as shown in Fig. 11.8a. Mark the position of the image *I* as much behind the mirror as the object is in front of it. Draw two rays of light *IAB* and *ICD* which enter the eye (see Fig. 11.8b). The lines behind the mirror should be dotted. This is the direction from which the light rays appear to come after being reflected by the mirror.

Complete the diagram by drawing the incident rays *SA* and *SC* which went to form the reflected rays (see Fig. 11.8c).

If the point source *S* is situated such that the perpendicular from it does not fall on the mirror (Fig. 11.9), it can still be considered to be in front of the mirror since diverging rays from it are able to strike the reflecting surface of the mirror. In the figure the widest possible incident beam one can obtain is enclosed between *SA* and *SC* which are incident rays on the extreme ends of the mirror. When the reflected rays *AB* and *CD* are drawn, the eye must be

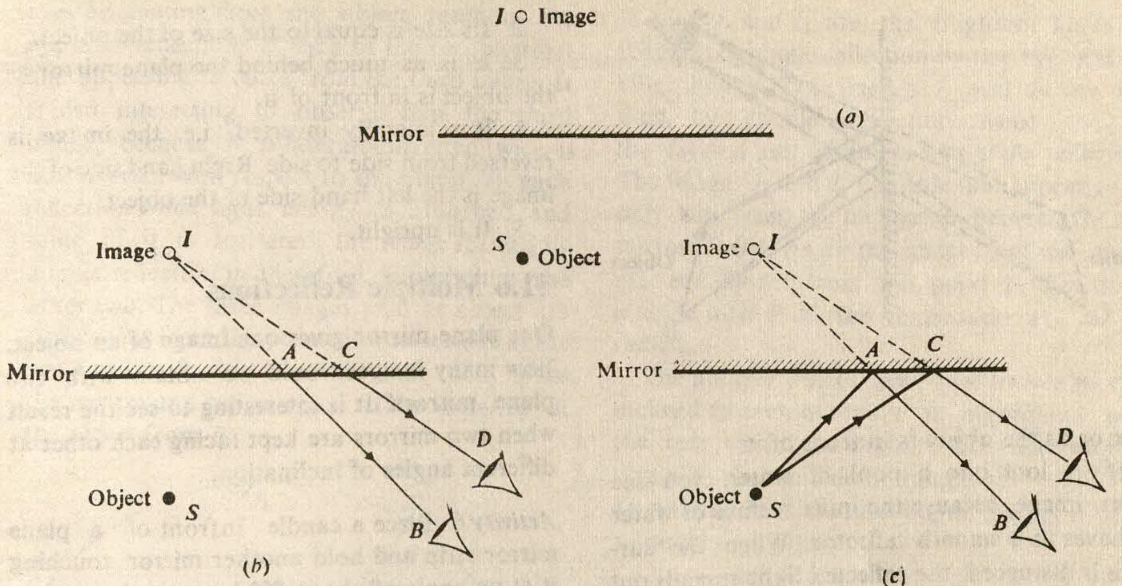


Fig. 11.8

placed between the two reflected rays to observe the image.

11.5 Image of an Extended Object

Consider a pencil, shown by an arrow *AB* (Fig. 11.10) placed in front of a mirror. The image can be located by simple geometrical construction. The images of points *A* and *B* can be located as *a* and *b* respectively, by taking two rays from each of the point sources incident upon the mirror and obtaining the reflected rays by the method described above. Thus by point to point correspondence the arrow *ab* gives the virtual, erect and equal sized image of *AB*. It will be seen that the image is as much behind the

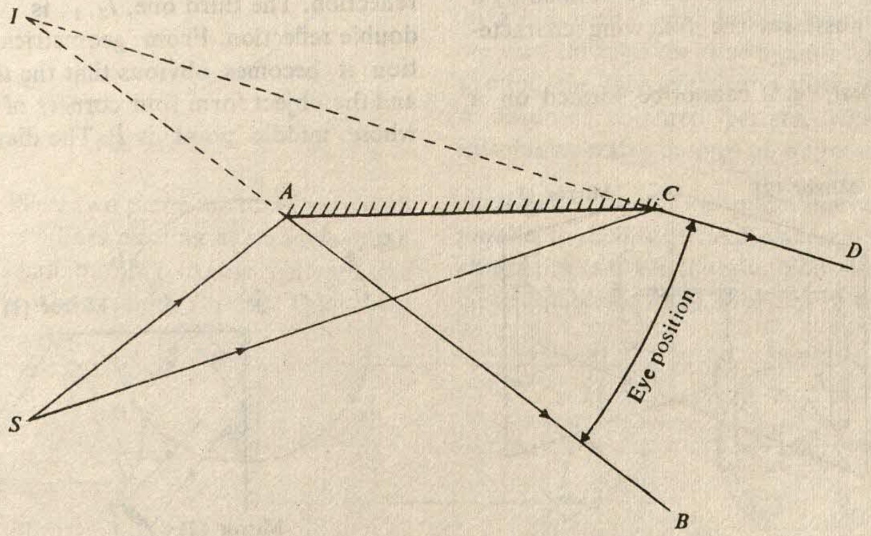


Fig. 11.9

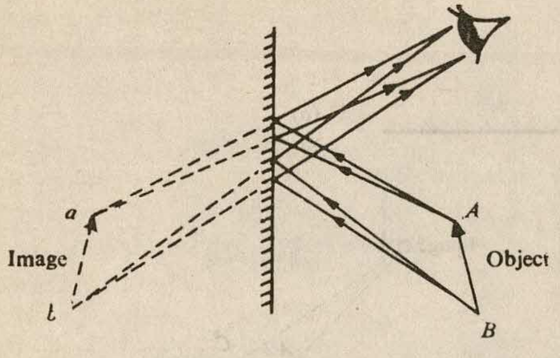


Fig. 11.10

mirror as the object is in front of it.

If you look into a pool of water, you see your image because the quiet surface of water behaves as a smooth reflector. When the surface is disturbed, the reflected light spreads out in many directions and no image is formed. Thus, the scattering of light caused by a rough surface does not produce an image, but makes the surface itself visible. Similarly, it is interesting to observe that a perfect plate glass mirror would itself be invisible; only the images of other objects would be seen in it and not the glass itself.

Characteristics of Image Formed by a Plane Mirror

You have learnt that the image formed by a plane mirror possesses the following characteristics.

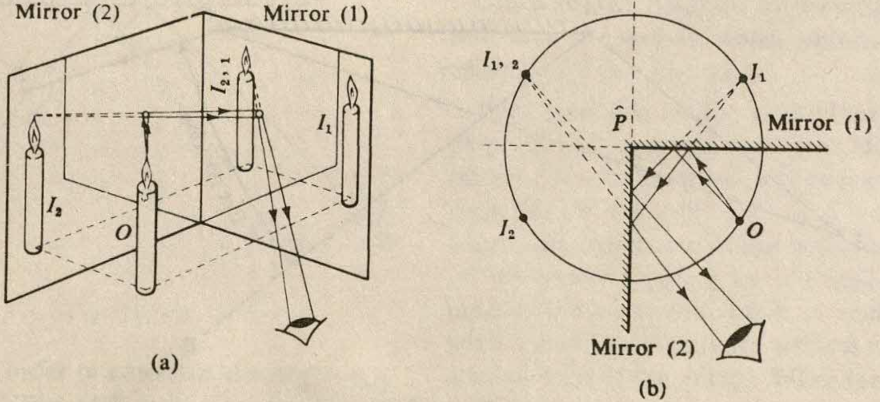
1. It is *virtual*, i e. it cannot be formed on a screen.
2. Its size is equal to the size of the object.
3. It is as much behind the plane mirror as the object is in front of it.
4. It is laterally inverted, i.e. the image is reversed from side to side. Right hand side of the image is the left hand side of the object.
5. It is upright.

11.6 Multiple Reflections

One plane mirror gives one image of an object; how many images would we obtain with two plane mirrors? It is interesting to see the result when two mirrors are kept facing each other at different angles of inclination.

Activity 6. Place a candle infront of a plane mirror strip and hold another mirror touching it at an angle of about 80° between them. How many images do you see? Now reduce the angle between the two mirrors gradually to 30°. Observe how the number of images changes.

When the angle between the two mirrors is 80°, you find four images in the two mirrors. As the angle is gradually increased from 80° to 90°, two of the images come together and merge into each other, and we see in all three images. Two of these images, I_1 and I_2 in Fig. 11.11, are formed by the two mirrors by ordinary reflection. The third one, $I_{2,1}$ is formed by double reflection. From geometrical construction it becomes obvious that the three images and the object form four corners of a rectangle whose middle point is P. The diagram shows



(a)

(b)

Fig. 11.11

rays originating from the object reaching the eye after reflections at each of the two mirrors, and appearing to come from the third image. It is also interesting to observe that the third image, because it is laterally inverted twice, is not inverted with respect to the object. At each reflection some light energy is absorbed and some of it is scattered; the image formed by double reflection is, therefore, fainter than the other two. The three images and the object are equidistant from the point of intersection of the two mirrors P; they lie on a circle with P as the centre and radius equal to the distance of the object from P.

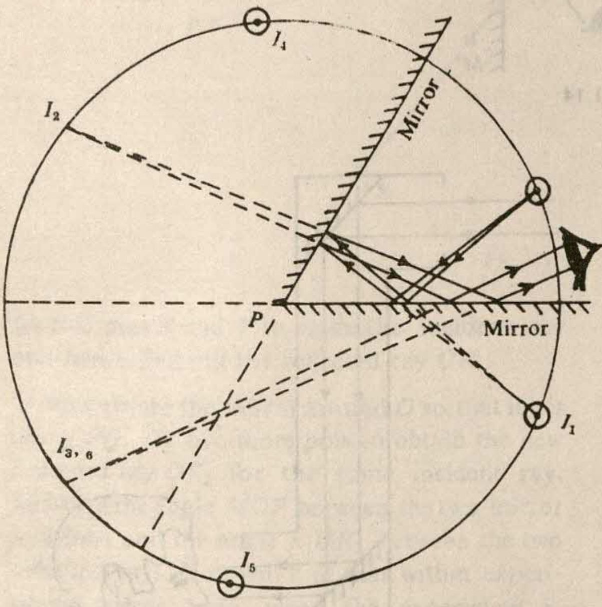


Fig. 11.12

Activity 7. Place two plane mirrors facing each other along two lines meeting at an angle of 60° and keep a small burning candle between the two. Observe the images formed. Two of the images, I_1 and I_4 are the brightest. These are formed by single reflection by the two mirrors (Fig. 11.12). The images I_2 and I_5 are formed by double reflection while $I_{3,6}$ is the faintest and is formed by triple reflection. The images I_3 and I_6 coincide and appear to be only one when the inclination between the two mirrors is 60°. As all the images and the object are equidistant from the point P, they lie on a circle with P as the centre and PO as the radius.

The number of images formed by two mirrors inclined to each other are in accordance with the rule that if the angle between the two mirrors is θ, the number of images $n \doteq (360/\theta - 1)$. n is raised to the next higher integer if it is a fraction.

11.7 Kaleidoscope

A kaleidoscope (Fig. 11.13) is an interesting toy which makes use of multiple reflections by plane mirrors held at 60° inclination. Three plane mirror strips of equal width and length are held tight inside a carboard tube so that they are inclined at 60° to each other. One side of the tube is blocked by coloured pieces of glass held between a transparent and a translucent glass plate. while the other end is blocked by a disc with a small hole to look inside. When we view through the tube against a bright background, the glass pieces and their images form a beautiful coloured pattern, which changes into innumerable designs as we rotate the tube.

Activity 8. Hold two plane mirrors roughly parallel to each other and place a pen cap or a chalk stick between the two. You will find a very large number of images formed in both mirrors

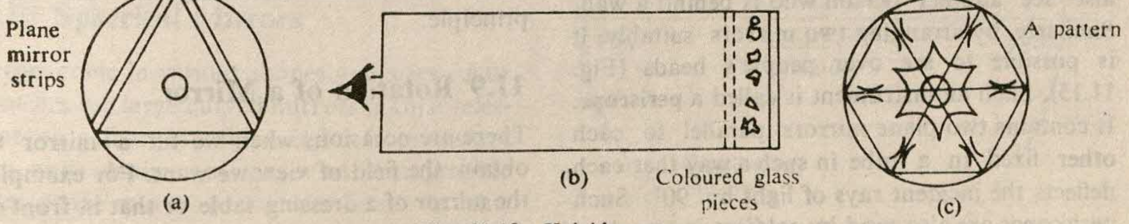


Fig. 11.13 Kaleidoscope

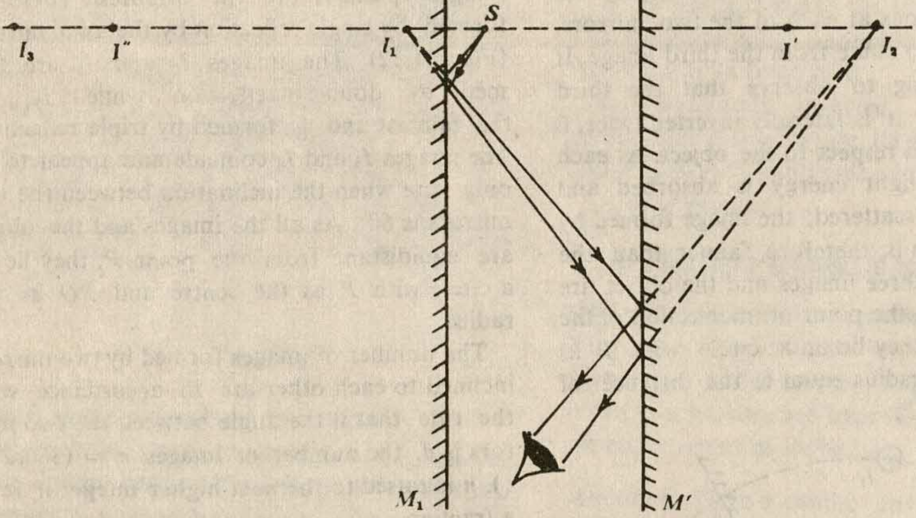


Fig. 11.14

due to multiple reflections. The ray diagram, Fig. 11.14, shows how the image I_2 of source S is seen by double reflection. For all practical purposes I_2 is the image of I_1 and is formed as much behind the mirror M' as I_1 is in front of the mirror. If the eye were not to obstruct these rays, they will be reflected once again by the mirror M_1 and appear to come from an image I_3 whose location will be as much behind M_1 as I_2 is in front of it. Thereby a series of images will result. However, such images will become less bright because of absorption of light at successive reflections. Barber shops often have mirrors facing each other fixed on opposite walls.

11.8 Periscope

If you stand in sunlight with a mirror in your hand, you can easily reflect light into a dark room. By arranging a mirror suitably you can also see another person who is behind a wall. Similarly, by arranging two mirrors suitably it is possible to see over people's heads (Fig. 11.15). Such an instrument is called a **periscope**. It contains two plane mirrors parallel to each other fixed in a tube in such a way that each deflects the incident rays of light by 90°. Such periscopes are also used by soldiers in trenches.

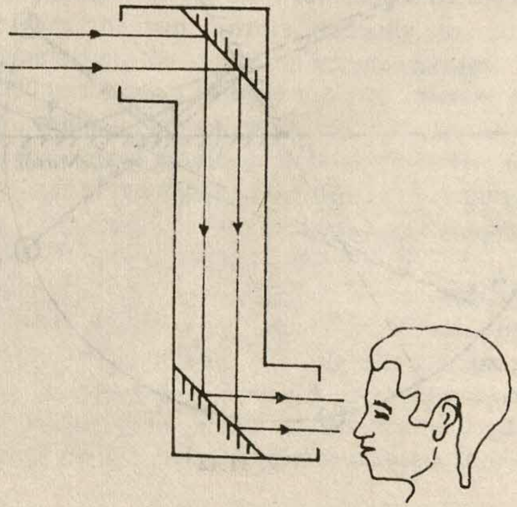


Fig. 11.15 Periscope

Submarine periscopes are actually more complicated but work essentially on the same principle.

11.9 Rotation of a Mirror

There are occasions when we tilt a mirror to obtain the field of view we want. For example, the mirror of a dressing table or that in front of the driver's seat in a car are rotated so that the rays reflected by the mirror reach the eye. How much should a mirror be rotated?

Activity 9. Draw on a sheet of paper two lines MN and PQ intersecting at O, which is taken as the point of incidence of a ray of light SO (Fig. 11.16). Place a plane mirror vertically with the mirrored surface on the line MN. Now fix two pins S and T to make the incident ray and hence find out the reflected ray OR_1.

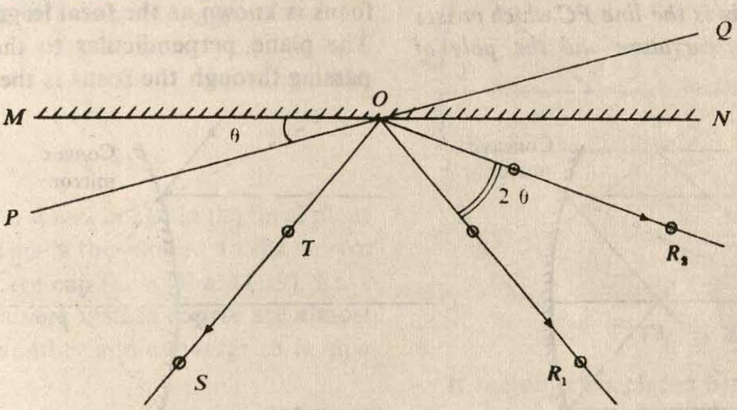


Fig. 11.16

Now rotate the mirror around O so that it lies along PQ. Fix two more pins to obtain the new reflected ray OR_2 for the same incident ray. Measure the angle MOP between the two mirror positions and the angle R_1OR_2 between the two reflected rays. You will find that within experimental error, even when the experiment is repeated with different angles between the two mirrors, this angle is half of the angle between the two reflected rays. *Thus, when a mirror is rotated through any angle, the reflected ray rotates through double the angle.*

11.10 Spherical Mirrors

Mirrors come in various shapes and sizes. Astronomers use large curved mirrors in their telescopes to gather the faint light from distant stars and obtain real images on photographic plates. Plane mirrors cannot be used for this purpose because they produce only virtual images. Curved reflectors are used in searchlights, headlamps of cars and scooters, and in torches. Drivers use curved mirrors in front of them to obtain a view of the traffic in the rear. All such mirrors obey the laws of reflection but it is their shape which makes all the difference in the nature of image obtained. Two such special mirrors which we shall study are the *spherical mirrors: concave* and *convex*. They are generally made by silvering a piece cut from a hollow glass sphere. If the piece is silvered on the outer surface, its inner (concave) surface is used for reflection and it is called a concave mirror, while if the inner surface is silvered, it is called a convex mirror because the convex surface will be the reflector of light (Fig. 11.17).

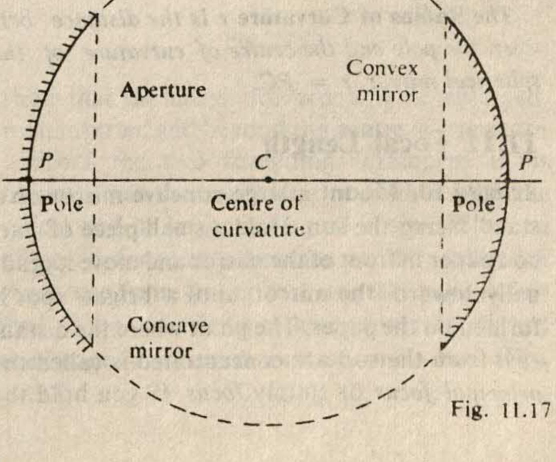


Fig. 11.17

It is necessary to be familiar with the following terminology before we discuss the formation of images in spherical mirrors.

The Centre of Curvature *C is the centre of the sphere of which the mirror forms a part.*

The Pole *P is the centre of the mirror which is used as a reference point for the measurement of various distances.*

The **Principal Axis** *is the line PC which passes through the centre of curvature and the pole of the mirror.*

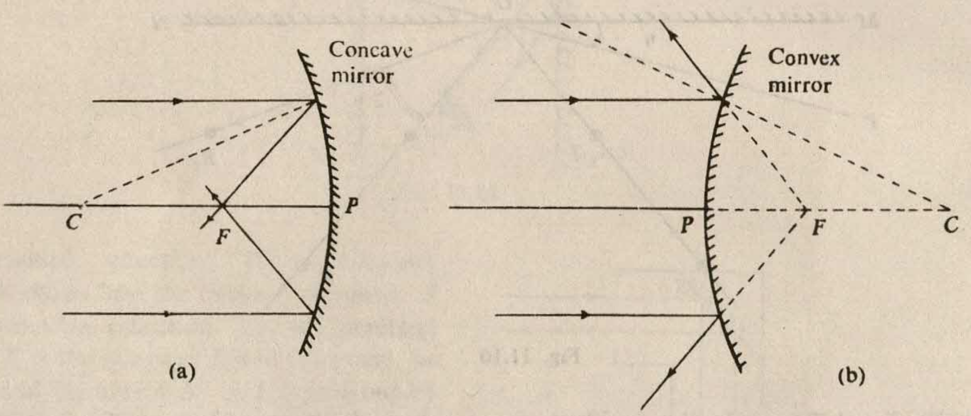


Fig. 11.18

The **Aperture** *is the width of the mirror and is measured by the distance between two opposite points on the edge of the mirror.*

The **Normal** *to the surface is the straight line passing through the point of incidence and the centre of curvature*; since the surface at the point of incidence is represented by a tangent to the circle at the point, the radius, being perpendicular to the tangent, is the normal.

The **Radius of Curvature** *r is the distance between the pole and the centre of curvature of the spherical mirror,* $r = PC$.

11.11 Focal Length

Activity 10. Mount a large concave mirror on a stand facing the sun. Hold a small piece of carbon paper in front of the mirror and move it gradually towards the mirror until a bright spot is formed on the paper. The point where the distant rays from the sun are concentrated is called the *principal focus* or simply *focus*. If you hold the paper steady, it gets warm and might start burning.

The principal focus *of a concave mirror is the point through which rays of light originally coming parallel to the principal axis pass, after reflection from the mirror* (Fig. 11.18a). Since the rays actually meet and can be taken on a screen, it is a real focus. The distance from the pole to the focus is known as the **focal length** of the mirror. The plane perpendicular to the principal axis passing through the focus is the focal plane.

In the case of a convex mirror the rays coming parallel to the principal axis diverge on reflection and appear to come from a point called the principal focus of the mirroı (Fig. 11.18b). The **principal focus** *of a convex mirror is an imaginary point behind the mirror where the rays of light coming parallel to its principal axis appear to meet after reflection from it.* Since the focus is virtual, therefore, the focal length of the convex mirror is negative. Numerically, the focal length of a spherical mirror is equal to half the radius of curvature.

11.12 Images Formed by a Concave Mirror

The nature, size and position of the image formed by a concave mirror changes according to the distance of the object from the mirror. For example, when an object is at very great distance, such as the Sun and stars, the rays of light are almost parallel to one another and

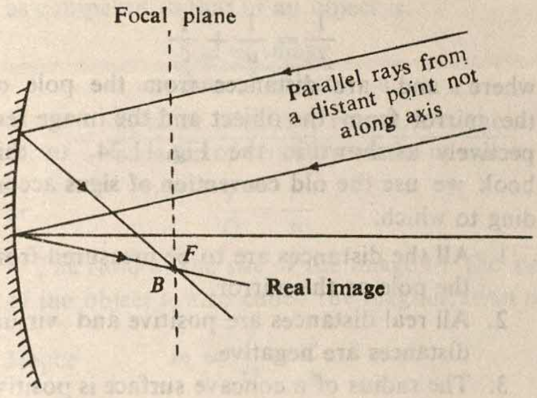


Fig. 11.19

converge to form a real image in the focal plane of the mirror. This is the closest to the mirror that any real image can form (Fig. 11.19). Rays of light from a very distant source are almost parallel to one another and converge to form a real image.

Activity 11. Place a lighted candle in a darkened room about 1 metre away from a concave mirror fixed on a stand. Hold a small piece of tissue paper in front of the mirror and move the paper gradually closer to the mirror till a clear image of the candle appears on the paper. You will notice that the image of the candle is up side down, smaller than the object and real.

In order to construct a ray diagram to locate the nature and position of the image, it is necessary to trace the path of at least two of the several rays which originate from a point source and strike the mirror surface. However, the most convenient rays whose path can be traced from the properties studied earlier are: (a) a ray from the source going parallel to the principal axis which after reflection passes through the focus (where the focus is mid-way between *C* ond *P*) (b) a ray going through the focus towards the mirror is reflected back parallel to the axis; and (c) a ray passing through the centre of curvature is reflected back along the same path.

Fig. 11.20 shows how the location and nature of the image can be found using these rays. It is observed that when the object is beyond the centre of curvature of the mirror, the image is formed between the focus and the centre of curvature; it is real, inverted and reduced in size as compared to the object.

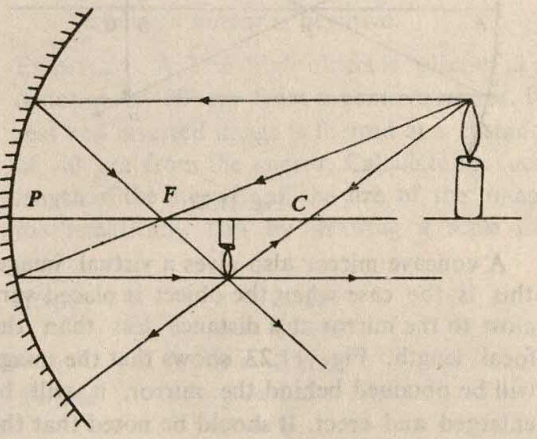


Fig. 11.20

If the object is placed between the focus and the centre of curvature, the principle of reversibility of light and the ray diagram (Fig. 11.21) show that the image formed will be enlarged, real, inverted and beyond the centre of curvature.

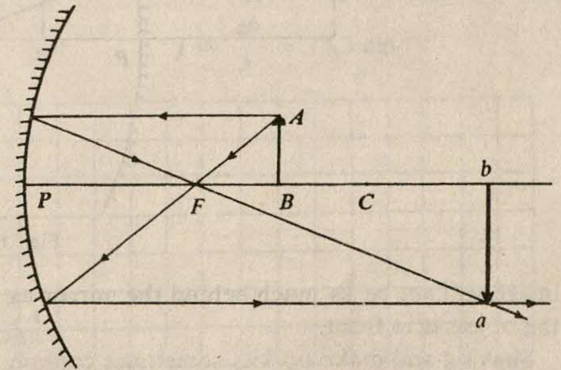


Fig. 11.21

From the two foregoing examples it is obvious that there will be a case when both the object and its image are equal in size. When an object is placed at a distance of the radius of curvature from the mirror, its real image is formed at the same distance away from the mirror; the image is inverted and of same size (Fig. 11.22).

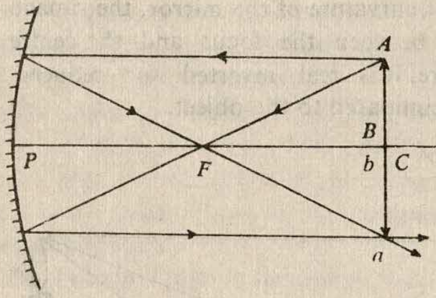


Fig. 11.22

A concave mirror also gives a virtual image; this is the case when the object is placed very close to the mirror at a distance less than the focal length. Fig. 11.23 shows that the image will be obtained behind the mirror, it will be enlarged and erect. It should be noted that the image will *not* be as much behind the mirror as the object is in front.

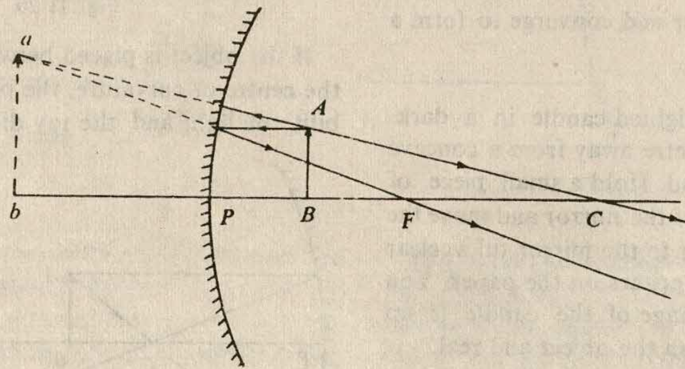


Fig. 11.23

Shaving and make-up kits sometimes contain a concave mirror which enables a magnified and upright image of the face to be formed.

11.13 The Mirror Formula

One of the ways to obtain information about an image is to construct a ray diagram. Another way is to make use of a mathematical relationship which we shall study now. A simple relationship exists between the distance of an object from the mirror u, the distance of the image from the mirror v, and the focal length f, of the mirror. This relationship is:

$$\frac{1}{f}=\frac{1}{u}+\frac{1}{v}$$

where u and v are distances from the pole or the mirror from the object and the image respectively as shown in the Fig. 11.24. In this book we use the old **convention of signs** according to which:

1. All the distances are to be measured from the pole or the mirror.
2. All real distances are positive and virtual distances are negative.
3. The radius of a concave surface is positive and that of convex surface is negative.

The mirror formula is applicable to all concave and convex mirrors for all distances of object and image. Another formula which can be helpful in calculating the size of an image

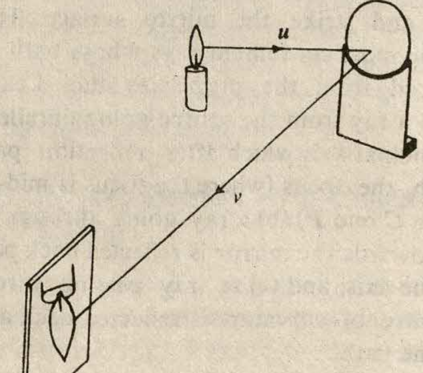


Fig. 11.24

as compared to that of an object is:

$$\frac{\text{Size of image}}{\text{Size of object}} = \frac{\text{distance of mirror from the image}}{\text{distance of object from the mirror}}$$

or $$\frac{I}{O} = \frac{v}{u}$$

The ratio of the size of the image to the size of the object is also called the magnification m.

Hence $$m = \frac{I}{O} = \frac{v}{u}$$

New Cartesian Convention

1. All distances are measured from the mirror as origin.
2. Distances measured against the incident light are negative and distances measured in the direction of the incident light are positive. In this convention the focal length of a concave mirror is negative and that of a convex mirror is positive.

Real-is-positive Convention

1. All distances are measured from the mirror as origin.
2. Distances of real objects and images are positive.
3. Distances of virtual objects and images are negative. In this convention focal length of a concave mirror is positive and that of a convex mirror is negative.

Example 1. **A 2 cm high object is placed at a distance of 20 cm from a concave mirror. Its real and inverted image is formed at a distance of 40 cm from the mirror. Calculate the focal length of the mirror and the size of the image mathematically and by drawing a scale diagram.**

Given $u = 20$ cm

$v = 40$ cm

$O = 2$ cm

To find $f = ?$

$I = ?$

Solution

Since $$\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$$

$$\therefore \quad \frac{1}{f} = \frac{1}{20} + \frac{1}{40} = \frac{2+1}{40} = \frac{3}{40}$$

or $$f = \frac{40}{3} = 13.3 \text{ cm}$$

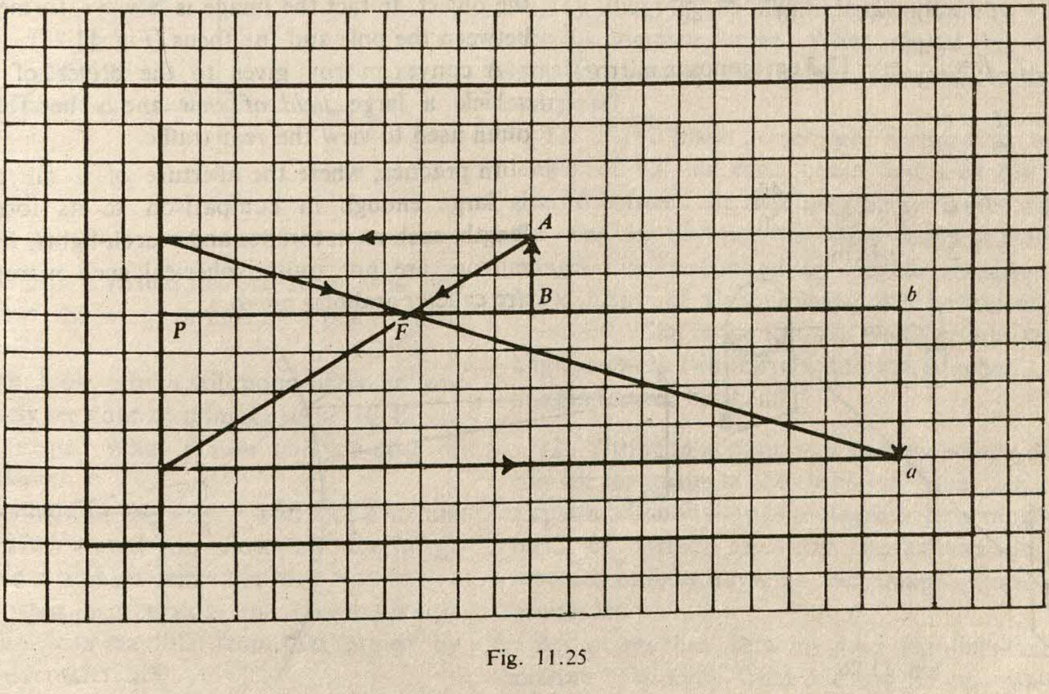


Fig. 11.25

Also as $\frac{I}{O} = \frac{v}{u}$

$$\therefore \quad I = \frac{v}{u} \times O = \frac{40\text{ cm}}{20\text{ cm}} \times 2\text{ cm}$$

$$= 4\text{ cm} \qquad \textit{Answer}$$

Draw the scale diagram as shown in Fig. 11.25. The scale is: 1 cm in the figure equal to 4 cm actual. Half centimeter graph paper has been used for the sake of convenience.

Measure PF and ab. They are found to be 3.3 cm and 1.0 cm respectively. Hence,

$$f = 3.3 \times 4 = 13.2\text{ cm} \qquad \textit{Answer}$$

$$I = 1.0 \times 4 = 4.0\text{ cm} \qquad \textit{Answer}$$

EXAMPLE 2. The following data is given in the new cartesian convention:

$u = -20$ cm

$v = -40$ cm

$O = 2$ cm

Find the focal length of the mirror and the distance of the image from it.

Solution

Since $\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$

$$\therefore \quad \frac{1}{f} = \frac{-1}{20} - \frac{1}{40} = \frac{-2-1}{40} = \frac{-3}{40}$$

$$f = \frac{-40}{3} = -13.3\text{ cm (concave mirror)}$$

Since $\frac{I}{O} = \frac{v}{u}$

$$\therefore \quad I = O \times \frac{v}{u} = 2 \times \frac{-40}{-20}$$

$$= 2 \times 2 = 4\text{ cm}$$

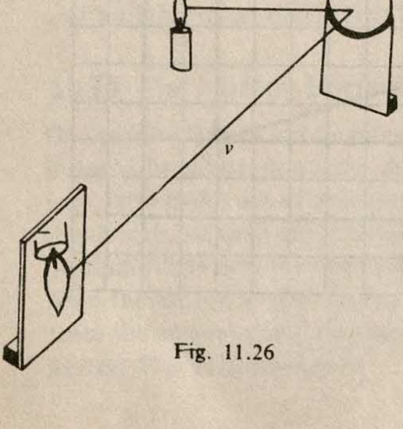


Fig. 11.26

11.14 Focal Length of Concave Mirror

Activity 12. Focus the image of a far off object such as the Sun, a tree or an electric pole on a screen. The mirror to screen distance gives the rough focal length of the mirror.

Place a lighted candle at about one and a half times the focal length from the mirror. Place a screen behind the candle and move it gradually away from the candle till you obtain a sharp image of the candle on it (Fig. 11.26). Measure the distances u and v of the candle and its image from the mirror.

Now substitute the values of u and v in the mirror formula $f = uv/(u+v)$ and calculate the focal length of the mirror. Repeat the experiment by varying the distance of the object from the screen. When u increases v decreases in such a way that the value of the focal length remains the same.

11.15 Image Formed by a Convex Mirror

Wherever the object may be placed, the image formed by a convex mirror is always behind the mirror, virtual, upright and smaller in size than the object. In fact the image is always formed between the pole and the focus (Fig. 11.27).

A convex mirror gives to the driver of a vehicle a large *field of view* and is therefore often used to view the rear traffic.

In practice, where the aperture of a mirror is large enough in comparison to its focal length; such as in torches and search-lights, the mirrors are not quite spherical; such mirrors are called parabolic mirrors.

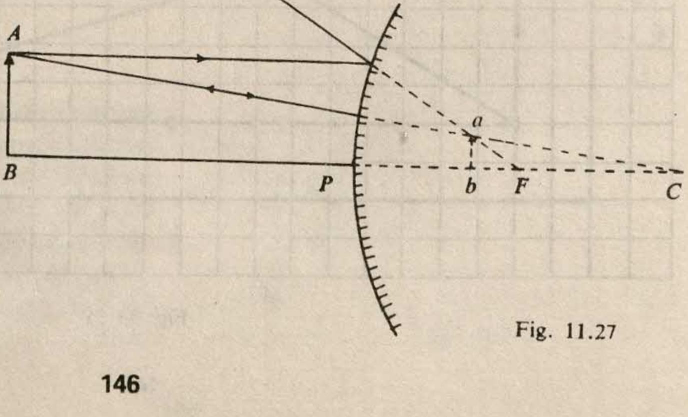


Fig. 11.27

QUESTIONS

1. What do you mean by reflection? Distinguish between regular and irregular reflection.

2. Explain the meaning of the terms (a) incident ray; (b) normal; (c) angle of reflection. State the two laws of reflection.

3. Give the various properties of an image formed by a plane mirror. Draw a line *AB* 2 cm high in front of a plane mirror. By constructing suitable rays and lines, locate the position of the image as seen by the eye. Measure the height of the image.

4. A plane mirror *AB* (Fig. 11.28) is standing vertically making an angle of 35° with a horizontal line *AC*. A ray of light *PQ* is incident on the mirror such that it cuts the line *AC* at a right angle (see Fig. 11.28). Calculate the angle between the incident and the reflected rays.

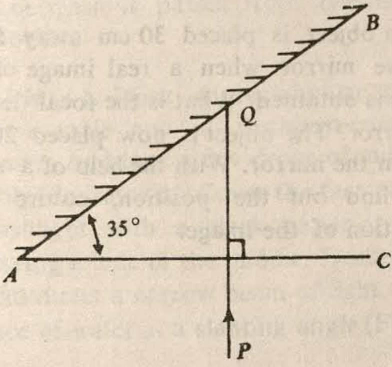


Fig. 11.28

5. What is a virtual image? How will you show that the image formed by a plane mirror is virtual?

If you look into a still pond of water, you can clearly see your own image in it. Is this a virtual image? What reason can you give for your answer?

6. Distinguish between a real and a virtual image. How would you show that the image formed in a pinhole camera is real?

7. In what respects does the image formed in a pinhole camera differ from that formed by a plane mirror?

8. *AB* is an arrow lying in front of a plane mirror. Take two incident rays from each of the points *A* and *B*, and show correctly the position of the image (see Fig. 11.29). Explain how the image gets laterally inverted.

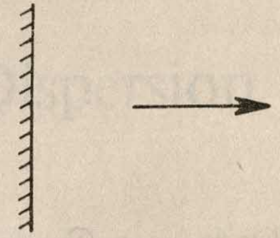


Fig. 11.29

9. A boy stands 2 m in front of a vertical plane mirror. A football is lying midway between him and the mirror. How far is the image of the football from him? If he steps back 1 m, how far will the image of the football be now from him?

10. A boy 1.6 m tall stands in front of a plane mirror fixed on the opposite wall. Draw a ray diagram to illustrate how the boy will see his complete image. What should be the smallest size of the mirror required for this purpose?

11. If two plane mirrors are inclined at an angle of 45° to each other and a candle is placed between the two, how many images will be seen in the mirrors? How many of these images will be formed by double reflection? How many of these images will be laterally inverted? What is the formula which relates the angle between two mirrors and the number of images formed by them?

12. Sitting in a chair in a barber's shop you can see the image of the back of your head. Explain with the help of a diagram the arrangement of mirrors necessary for this and show the path of light rays. Is the image laterally inverted?

An object lies between two parallel plane mirrors 1 cm away from one and 1.5 cm away from the other. Mark clearly on a diagram the positions of at least six images.

13. M_1 and M_2 are two plane mirrors held at right angles to each other (Fig. 11.30). A source is placed 2 cm away from M_2 and 4 cm from M_1. The point E is 6 cm away from M_2 and 2 cm from M_1. Draw three incident rays from S so that after reflection they pass through E.

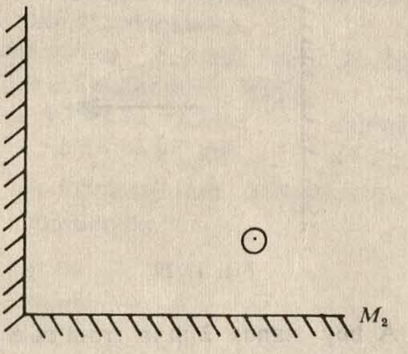


Fig. 11.30

14. With the help of a suitable diagram explain the meaning of the terms centre of curvature, pole, principal axis and aperture of a concave mirror.

15. What do you mean by the principal focus and the focal length of a concave mirror? Illustrate your answer with a ray diagram. Give examples where this information of focus and focal length of a concave mirror are used.

16. State the laws of reflection and draw diagrams to show that these laws hold good in the formation of the image of a point object both in the case of a concave and a convex mirror.

17. What is the relation between the distance of an object and its image from a concave mirror, and its focal length?

18. What kind of mirror should be used and how should an object be placed to produce (a) a small real image; (b) an enlarged real image; (c) a real image of same size; (d) a virtual image of same size; and (e) a small virtual image?

19. A 5 cm tall object is placed on and perpendicular to the axis of a concave mirror. When its distance from the mirror is 15 cm it produces an erect image 15 cm in height. Draw a ray diagram and find (a) the position of the image; and (b) the radius of curvature of the mirror.

20. An object is placed 30 cm away from a concave mirror when a real image of the same size is obtained. What is the focal length of the mirror? The object is now placed 20 cm away from the mirror. With the help of a scale diagram find out the position, nature and magnification of the image.

12

Refraction and Dispersion

Would you imagine that the twinkling of stars and the sparkling of a diamond have something in common? The grand spectacle of a rainbow after a shower, the blueness of the sky on a clear day and the reddish sky at sunset are based upon the fact that light deviates from its path when it passes from one medium into another.

Activity 1. Place a rectangular glass trough on a table and fill it almost completely with water. Add to it a few drops of milk or preferably 'flourescein'. Cover the face of a powerful flashlight with a black paper or a cardboard having a hole in the middle. Darken the room and direct a narrow beam of light on the surface of water at a slanting angle (Fig. 12.1).

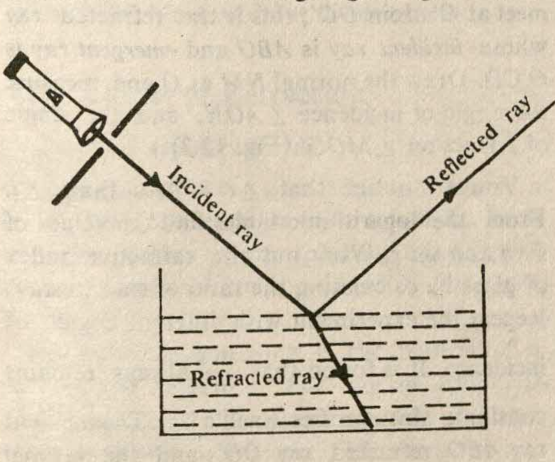


Fig. 12.1

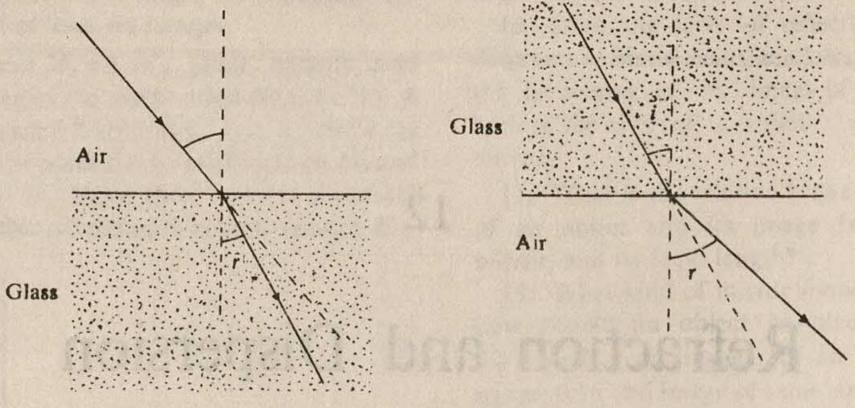
You will notice that a part of the light is reflected and most of it passes through water bending at the surface to follow another path along a straight line. This bending is called *refraction.* Now hold the flashlight vertically above the trough so that the light is incident normally on the surface; you will notice that the light is not bent when it enters the water.

The bending of light rays as they pass from one medium into another is called **refraction.** On entering water from air a ray of light bends towards the normal. If the light goes from water to air, then according to the principle of reversibility of light, it bends away from the normal.

12.1 Refraction and the Speed of Light

The velocity of light in air (or vacuum) is 3×10^8 m/s, and in glass and water is 2×10^8 m/s and 2.2×10^8 m/s respectively. Water and glass are 'slower mediums' than air and are called optically denser. *Optical density* is a property of a transparent material; it is a measure of the speed of light through the material.

A ray of light going from an optically rarer medium, such as air, to a denser medium, such as glass, slows down and changes its direction towards the normal (Fig. 12.2a), while a ray of light going from a denser medium to a rarer medium is speeded up and bends away from the normal (Fig. 12.2b). Thus refraction is caus-



(a) Fig. 12.2 (b)

ed by the change in the speed of light as it passes from one medium to another of different optical density.

The speed of light in different substances varies; therefore, different substances have different abilities to bend or refract light. We call this bending ability of a material its *index of refraction* or *refractive index*. Refractive index is the ratio of the speed of light in vacuum to that in the medium.

$$\mu = \frac{\text{speed of light in vacuum}}{\text{speed of light in the medium}}$$

The speed of light in air is almost as much as that in vacuum. For practical purposes, therefore, the speed in air is taken instead of that in vacuum. Refractive index is a specific property for a given medium. The refractive index for diamond is 2.4; what would be the speed of light as it passes through diamond?

12.2 Laws of Refraction

The extent by which a ray bends depends not only on the refractive index of the medium but also on the angle of incidence. William Snell for the first time experimentally found out that *the ratio of the sine of the angle of incidence to the sine of the angle of refraction is a constant and is equal to the refractive index of the medium.* This is called the **Snell's Law of Refraction.**

$$\mu = \frac{\text{sine of angle of incidence}}{\text{sine of the angle of refraction}}$$

$$= \frac{\sin i}{\sin r}$$

The second law of refraction states that the incident ray, the refracted ray and the normal at the point of incidence lie in the same plane.

12.3 Determination of Refractive Index

Activity 2. Place a rectangular glass block on a white sheet of paper fixed on a soft board and trace its outline. Fix two pins A and B about 5 cm apart so that the line joining them is inclined to the block at about 70°. Look from the other side and fix pins C and D such that they are in line with the images of A and B as seen through the block. Remove the block and join AB to meet the block at O, and DC to meet at O'. Join OO'; this is the refracted ray whose *incident ray* is ABO and *emergent ray* is $O'CD$. Draw the normal NM at O and measure the angle of incidence $\angle AON$, and the angle of refraction $\angle MOO'$ (Fig. 12.3).

You will notice that $\angle r$ is less than $\angle i$. From the logarithmic tables find the values of sin i and sin r. Work out the rafractive index of glass by calculating the ratio of sin i to sin r. Repeat the experiment with different angles of incidence. It is found that $\frac{\sin i}{\sin r}$ always remains constant; this verifies Snell's law. The incident ray ABO, refracted ray OO' and the normal MON are all in the plane of the paper.

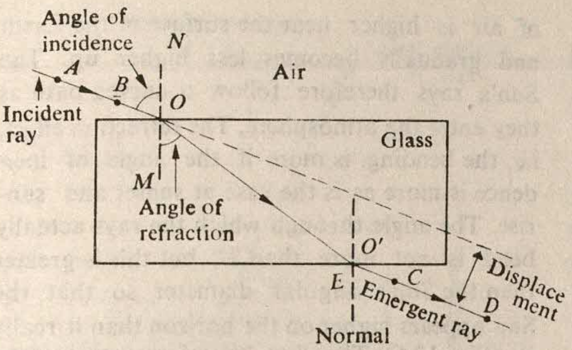


Fig. 12.3 Refraction by a rectangular block

12.4 Displacement

Now produce line *ABO* and check whether it is parallel to the emergent ray. (How will you find this out?) While passing through the glass block, the ray got displaced from its original path but remained parallel to it. The perpendicular distance (Fig. 12.3) between the incident ray produced and the emergent ray is called the **lateral displacement**.

Activity 3. Repeat the experiment with a glass block of greater thickness *t*, and with different angles of incidence *i*. You will find that the displacement increases with increase of *t* and *i*, but in each case the emergent ray is parallel to the incident ray. In the event when the incident ray is normal on the glass block, i.e. when the angle of incidence is zero, the ray passes straight through the block without displacement.

12.5 Effects of Refraction

1. *Real and Apparent Depth*

On looking through a glass block placed on a book, the print appears to be raised up. Similarly, any optically denser material, when viewed from a rarer medium appears to be less deep, see Fig. 12.4.

S is a point object lying at the bottom of a pond of real depth *SO*. The ray of light *SO* coming along the normal emerges out of water undeviated and goes along *OR*. Another ray *SA* bends away from the normal and goes along *AB*. The two emergent rays appear to come from O_1, hence O_1 is the virtual image of *S* and OO_1 is the apparent depth which is less than the real depth *OS*. It shows that ponds appear shallower than what they actually are. It can be mathematically proved that

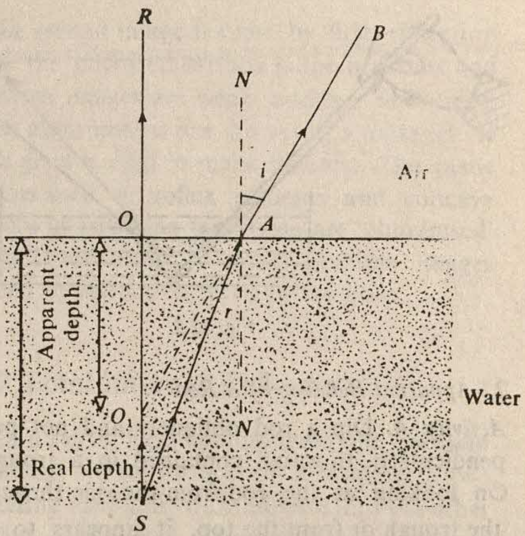


Fig. 12.4

$$\mu = \frac{\text{real depth of water}}{\text{apparent depth}}$$

EXAMPLE 1. A coin is placed at the bottom of a tall cylinder and water is poured into it to a depth of 16 cm. Find how far the coin will appear to be from the surface when the refractive index of water is 4/3.

Given Real depth = 16 cm

$$\mu = \frac{4}{3}$$

To find Apparent depth = ?

Solution

Since $$\mu = \frac{\text{real depth}}{\text{apparent depth}}$$

$$\frac{4}{3} = \frac{16}{\text{apparent depth}}$$

or $$\text{Apparent depth} = 16 \times \frac{3}{4} = 12 \text{ cm}$$

Answer

The coin will appear to be raised by about 4 cm.

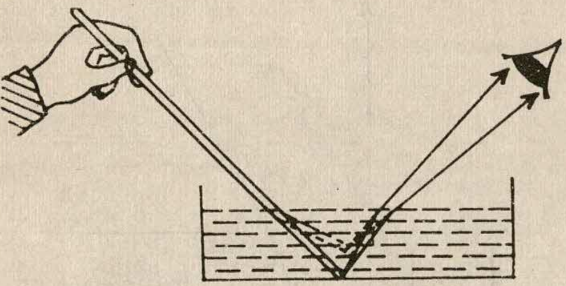


Fig. 12.5

2. *Apparent Bending of a Rod*

Activity 4. Dip a rod obliquely and not perpendicularly, in water contained in a trough. On looking at the rod from the side through the trough or from the top, it appears to be bent at the surface of water (Fig. 12.5).

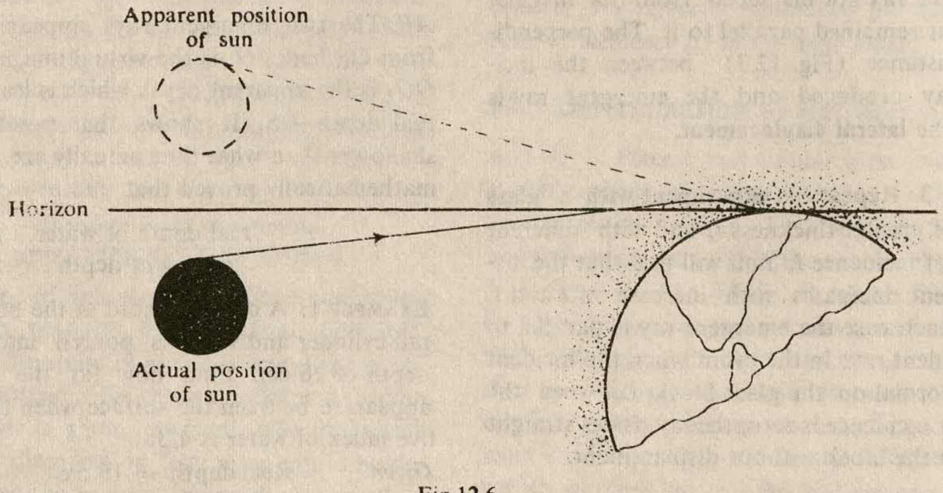


Fig 12.6

Rays of light coming from the various points of the portion of the rod in water refract away from the normal as they emerge from water into air. Each point on the dipped part of the rod, therefore, has a corresponding image point. The rod therefore appears bent at the surface to our eyes.

3. *Atmospheric Refraction*

The refractive index of air of normal density is about 1.0003 relative to vacuum. Thus, rays of light coming from the Sun through space bend very slightly towards the normal. The density of air is higher near the surface of the Earth and gradually becomes less higher up. The Sun's rays therefore follow a curved path as they enter the atmosphere. The refraction effect, i.e. the bending, is more if the angle of incidence is more as is the case at sunset and sunrise. The angle through which the rays actually bend is not more than 2°, but this is greater than the Sun's angular diameter so that the Sun appears higher on the horizon than it really is (Fig. 12.6). The Sun, therefore, appears to set several minutes after it has actually sunk below the horizon, and can be seen a few minutes before it actually rises above the horizon.

Unless a star is directly above and the rays from it are normal to the atmosphere, atmospheric refraction causes an angular displacement of nearly 1/2° and a star is not where it appears to be (Fig. 12.7). This effect has to be taken into account by astronomers and nagivators.

The atmosphere consists of several moving masses of air, some hot and some cold, some dense and some rarer. When light from a distant star enters the Earth's atmosphere, it is bent as it passes from one mass of air to another. The masses themselves are in motion. This gives rise to the *twinkle* in stars. The wriggling appearance of objects through air above hot

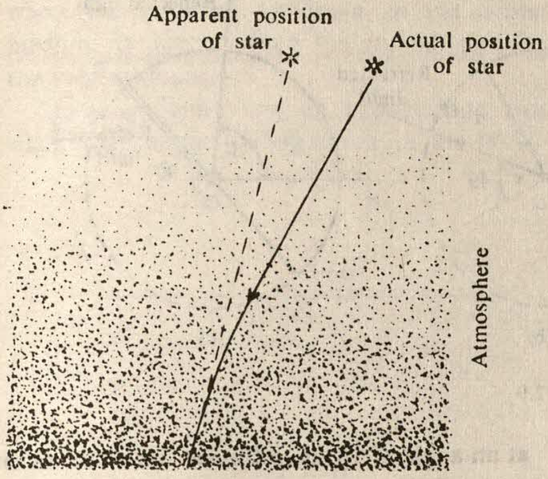


Fig. 12.7

sand, radiators or fire is similar to the twinkling of stars.

12.6 Multiple Images in a Thick Mirror

Mirrors are ordinarily made by silvering the back face of a glass plate. They form multiple images because of reflection from the front face of the glass and from the mirrored surfaces as shown in Fig. 12.8.

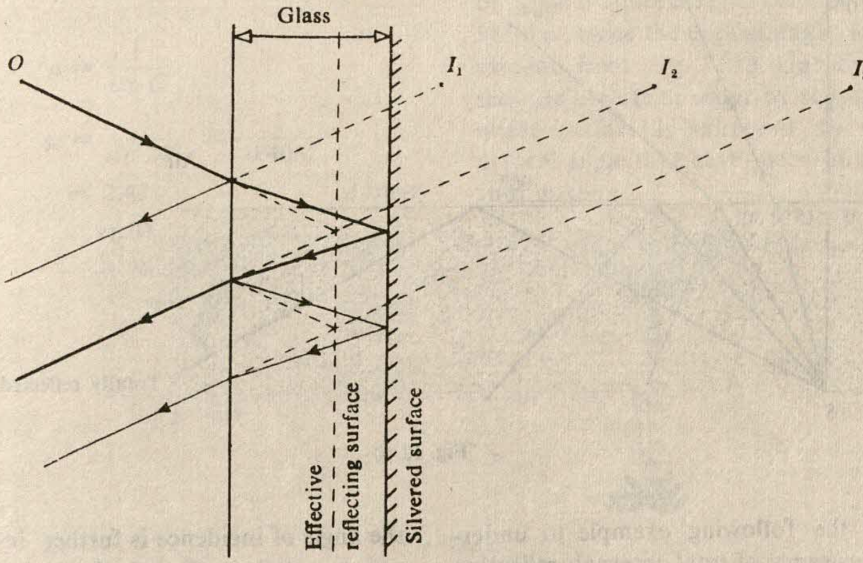


Fig. 12.8

The second image formed by first reflection from the mirrored surface is the brightest and the other images are weak and go unnoticed. These extra images are, however, a nuisance if thick glass is used in plane mirrors. The plane mirrors used in reflex cameras and concave mirrors of reflecting telescopes are 'aluminised' on the front surface to avoid multiple images formed by refraction through the glass.

12.7 Total Internal Reflection

When a ray of light coming from one medium is incident on the surface of separation of two refracting mediums, transmission into the other medium is expected. However, this does not happen under certain special conditions.

Activity 5. Place a semicircular glass block on a white sheet of paper and draw a complete circle around it. Allow a narrow beam of bright light to fall normally on the glass block such that the refracted beam passes through the centre of the circle (Fig. 12.9). Rotate the block gradually around the centre. You will observe that the proportion of reflected light increases as the angle of incidence increases. Eventually

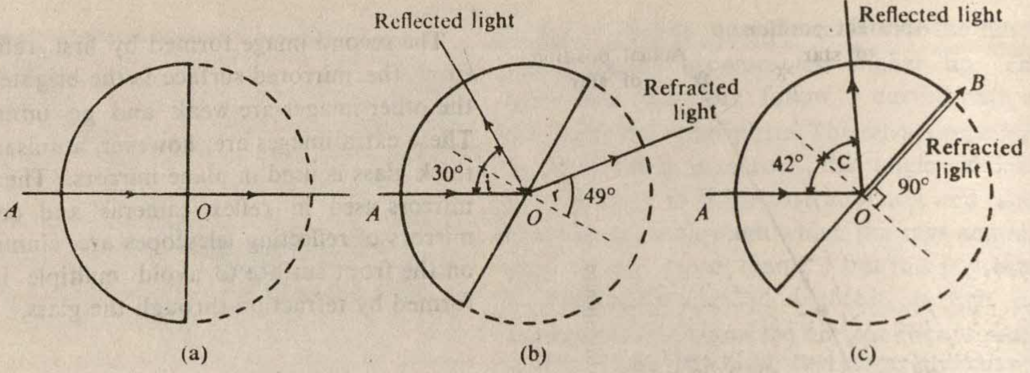


Fig. 12.9

the refracted ray emerges grazing along the surface and the angle of refraction is 90°.

The limiting angle of incidence in a denser medium for which the angle of refraction in air (or vacuum) is 90° is called **critical angle**. It will be found from the above experiment that the critical angle for glass is roughly 42°. On further rotation, the refracted ray disappears and the incident ray is *totally internally reflected* inside the glass block according to the laws of reflection.

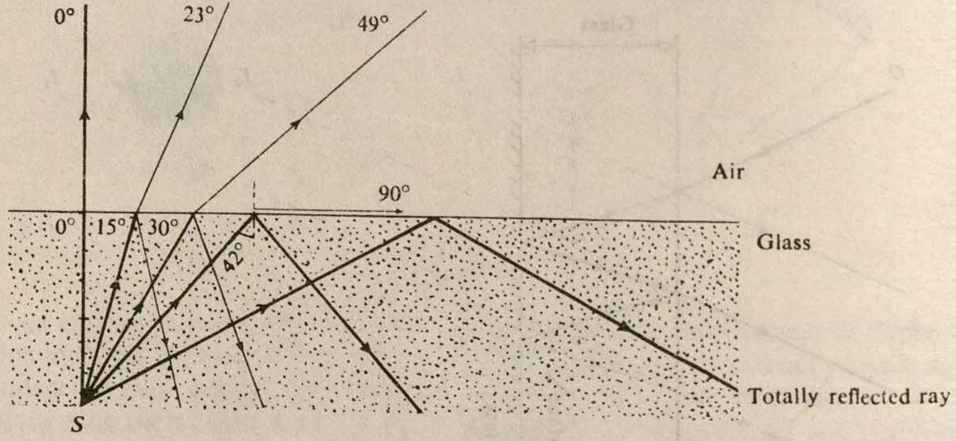


Fig. 12.10

Consider the following example to understand the occurance of total internal reflection in a medium. Fig. 12.10 represents a glass block with a point source *S* giving out rays of light which are incident at the air-glass interface at various angles. For example, the ray incident at an angle of 15° is refracted into air at an angle of 23° according to the laws of refraction; there is also some partial reflection.

As the angle of incidence increases, the angle of refraction also increases while the partially reflected beam becomes stronger. When the angle of incidence is 42° a weak refracted ray grazes along the surface while most of the light is reflected. This angle of incidence in glass for which the angle of refraction in air is 90°, is called the critical angle for glass. When the angle of incidence is further increased, the ray is totally reflected back in glass. This phenomenon is called *total internal reflection*. Total internal reflection occurs when the ray of light is incident from a denser medium on the surface of separation of two mediums, and when the angle of incidence in the denser medium is greater than the critical angle for the two mediums.

Applying Snell's law in the limiting case when the angle of refraction in air is 90°

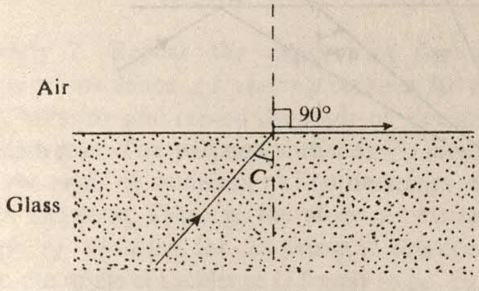


Fig. 12.11

(Fig. 12.11) and using the principle of reversibility of light, we obtain

$$\mu_{\text{glass}} = \frac{\sin i}{\sin r} = \frac{\sin 90^\circ}{\sin C} = \frac{1}{\sin C}$$

EXAMPLE 2. The critical angle of diamond is 24°; calculate its refractive index.

Given $C = 24^\circ$

To find $\mu = ?$

Solution

Since $\mu = \dfrac{1}{\sin C}$

$\therefore \quad \mu = \dfrac{1}{\sin 24^\circ} = \dfrac{1}{0.4067}$

$= 2.43$ *Answer*

12.8 Applications of Total Internal Reflection

If the refractive index of diamond is 2.42, its critical angle from the above formula is 24.5° When a ray of light enters a diamond through one face, it undergoes multiple internal reflections due to the extremely small critical angle. This gives diamond its characteristic sparkle. In practice, diamonds are cut so as to maximise the number of internal reflections. The brilliance of diamonds is thereby greatly increased.

Mirages are caused by total internal reflection produced by warm air over sand or road. On a hot day the air above them is considerably hotter, and consequently rarer, than the air higher up. A ray of light, say from a tree, travelling downwards is gradually refracted from cooler to hotter layers of air and the angle of incidence increases (Fig. 12.12). The ray of light travels in a curved path and ultimately gets totally reflected near the surface from a hot layer. This gives the impression that the road is wet and there is a pool of water on it.

Mirror Effect in Water

At whatever depth a diver in water may be, if the surface is calm he has a full view of everything above the water; however, the 180° field of view is squeezed to a cone of approximately 98°, i.e., twice the critical angle for water as is evident from Fig. 12.13. Outside this range he sees the objects in water by reflection, as if the water surface is mirrored. In Fig. 12.13 the critical angle rays have been drawn from air into water.

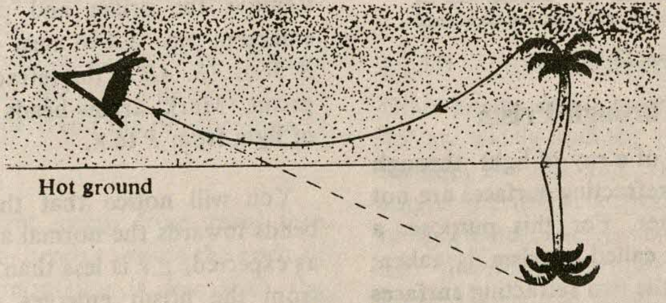


Fig. 12.12

An empty test tube placed slanting in water and viewed from above will appear mirrored because total internal reflection takes place between the water-air interface outside the test

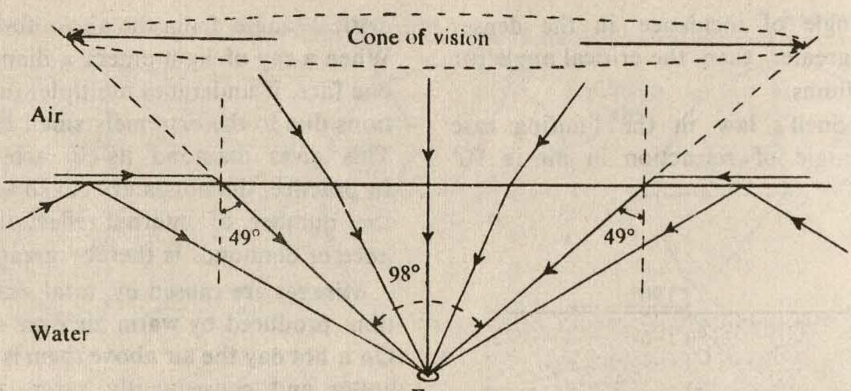


Fig. 12.13

tube (Fig. 12.14). If the tube is filled with water it no longer gives the mirror effect. What would you expect to see if the tube is half filled with water?

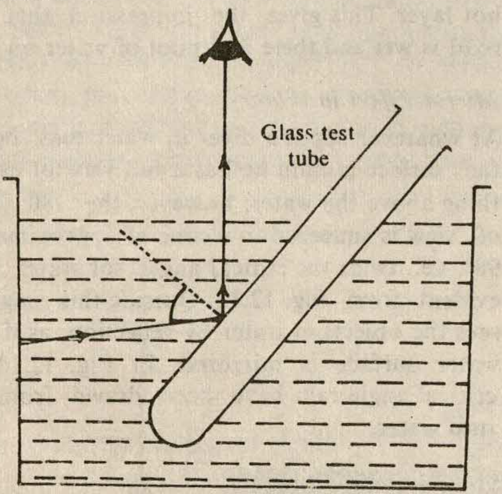


Fig. 12.14

12.9 Refraction Through Prism

Let us study the path of a ray of light through glass when the two refracting surfaces are not parallel to each other. For this purpose, a triangular glass block called a **prism** is taken; faces *XY* and *XZ* are the two refracting surfaces inclined to each other. The face *YZ* is called base of the prism (Fig. 12.15).

Activity 6. Draw the outline of a prism on a white sheet of paper; fix two pins *P* and *Q* to form the incident ray and draw a normal at *A* where the incident ray meets the face *XY*. With the prism in position, look from the side of the face *XZ* towards the prism and fix two more pins *R* and *S* in line with the images of *P* and *Q*. Remove the prism and pins, and draw the emergent ray *SR* to meet the prism outline at *B*. Join *AB*. *AB* is the refracted ray through the prism. Mark arrow-heads to indicate the path of light from *P* to *R*.

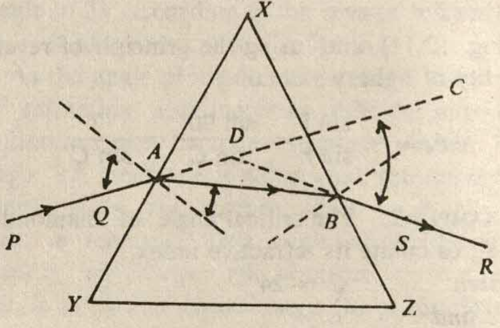


Fig. 12.15 Prism

You will notice that the incident ray *PA* bends towards the normal as it enters the glass; as expected, $\angle r$ is less than $\angle i$. When the light from the prism emerges into air at *B*, the emergent ray *SR* bends away from the normal drawn at *B*.

Deviation

You will observe that if *PQ* is produced to

C, the emergent ray *SR* is not parallel to it. If *RS* is produced backwards to meet *PC* at a point *D*, ∠*CDS* can be measured. This angle between the incident ray and the emergent ray is called the **angle of deviation**.

Activity 7. Repeat the experiment for the angle of incidence ∠*i* varying between 30° and 70°. Measure and record the angle of deviation in each case. You will notice that as ∠*i* increases, the angle of deviation at first decreases and then increases. There is therefore a *minimum angle of deviation* for the prism; in this condition the angle of incidence is found to be equal to the angle of emergence. If the experiment is repeated with a prism of different angle, the angle of deviation will be seen to change; if ∠*X* is less, the angle of deviation also becomes less (Fig. 12.16). In the limiting case when ∠*X* = 0, and the prism becomes a plane glass slab, the angle of deviation is zero and the emergent ray is parallel to the incident ray, as we have already seen.

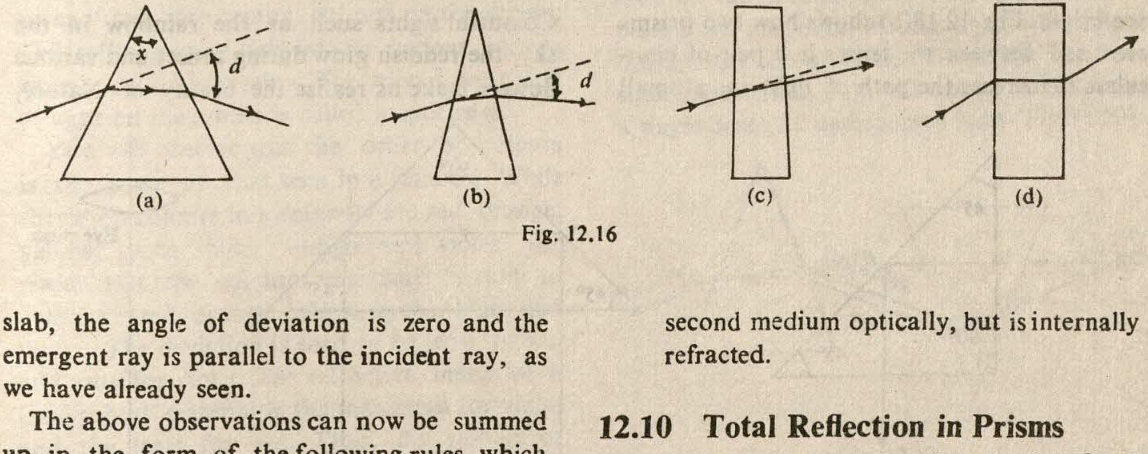


Fig. 12.16

The above observations can now be summed up in the form of the following rules, which would help to understand the phenomenon of refraction:

(a) A ray of light going from rarer into denser medium bends towards the normal; the angle of refraction is less than the angle of incidence in such a case.

(b) A ray of light emerging from an optically denser medium into an optically rarer medium bends away from the normal; in such a case, the angle of emergence is more than the internal angle of incidence.

(c) When the incident ray is normal to the second medium, it is transmitted without change of direction; the angle of incidence and the angle of refraction are both zero.

(d) In case of parallel refracting surfaces (as in a glass slab), the incident and emergent rays are parallel to each other; the ray undergoes displacement without deviation.

(e) In case the two refracting surfaces are not parallel (as in a prism), the incident and emergent rays are not parallel to each other; the ray suffers deviation. The amount of deviation depends upon the angle between the two refracting surfaces and the refractive index of the material.

(f) In case of light going from an optically denser to an optically rarer medium, when the internal angle of incidence is greater than the critical angle for the two mediums, the ray is not refracted into the second medium optically, but is internally refracted.

12.10 Total Reflection in Prisms

Glass prisms which have angles of 90°, 45° and 45° are widely used for turning a ray of light through 90° and 180°. Fig. 12.17 shows how single internal reflection is achieved; the ray of light enters and leaves the prism normally and therefore goes undeviated. Internal reflection takes place at the air-glass interface at the point of incidence *P* because the angle of incidence, which is 45°, is greater than the critical angle for glass.

Fig. 12.17(b) gives an idea how a ray can be doubly internally reflected. In this case the

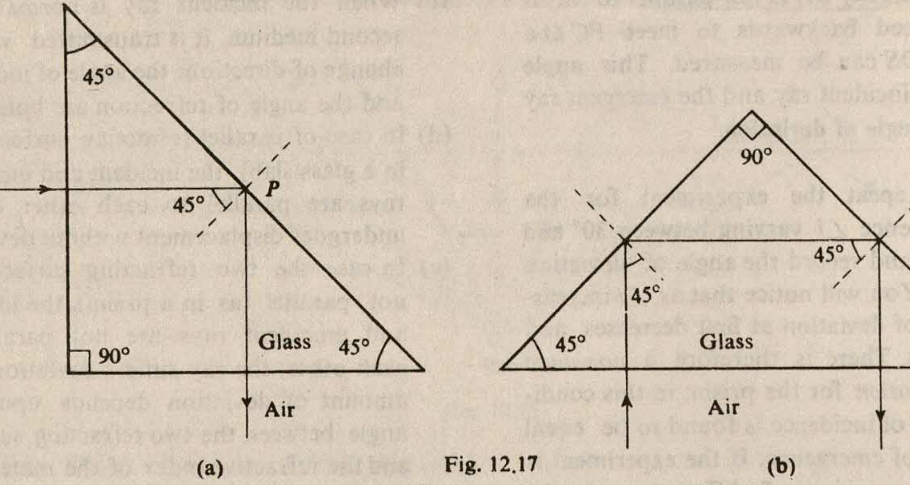


Fig. 12.17

prism behaves like two prisms of Fig. 12.17(a) in contact. Glass prisms are preferred over plane mirrors in periscopes (Fig. 12.18a) because there is very little scattering and no multiple reflections take place, so that the images formed are bright. Fig. 12.18(b) shows how two prisms are used between the lenses in a pair of binoculars to increase the path of light in a small distance. The final image is unchanged in other respects.

12.11 Dispersion

Colourful sights such as the rainbow in the sky, the reddish glow during sunset and various flowers make us realise the beauty of Nature;

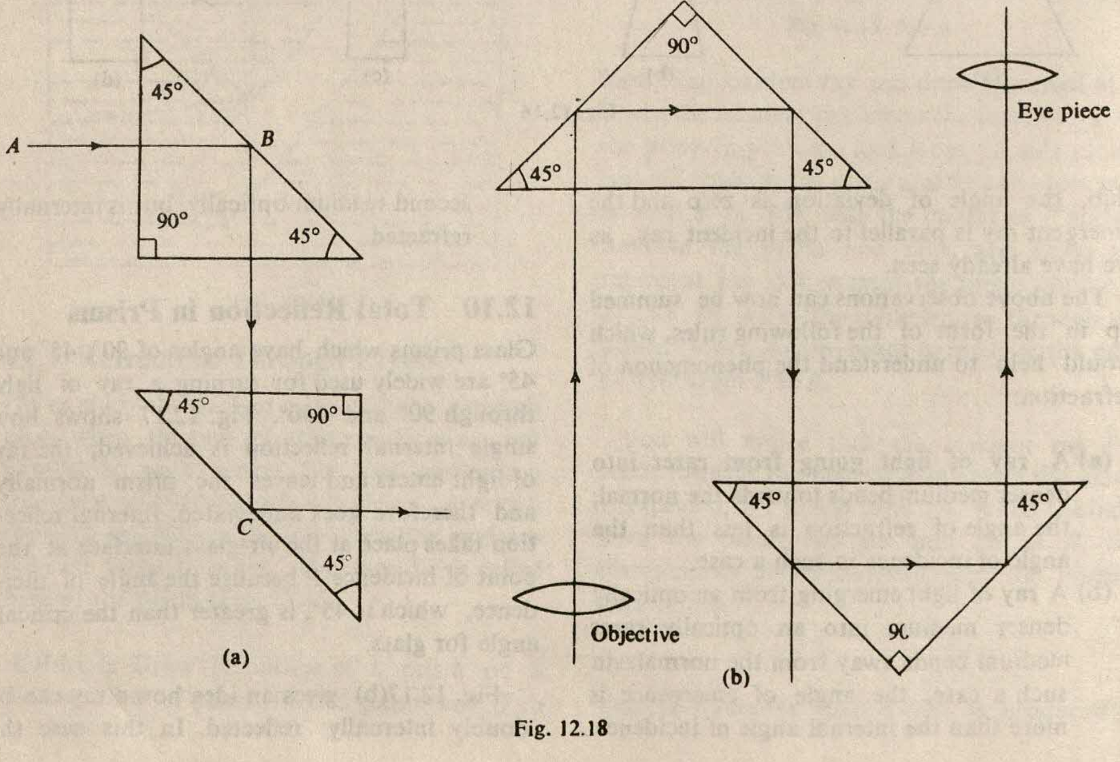


Fig. 12.18

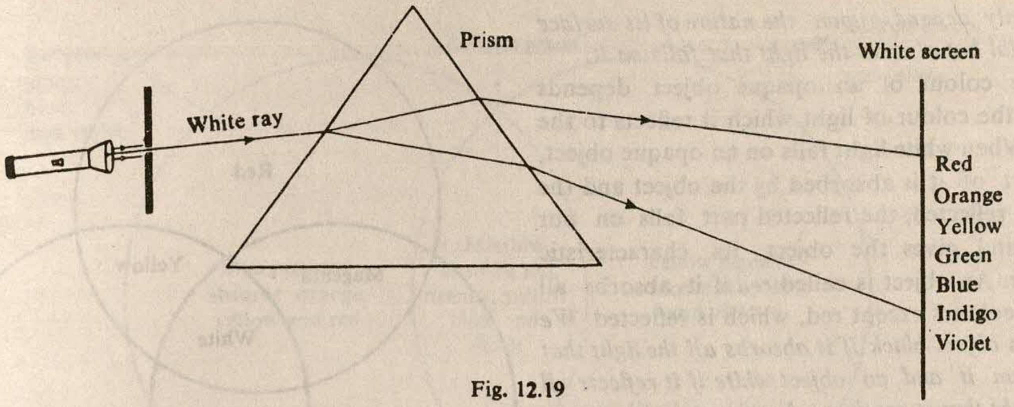


Fig. 12.19

we owe this to the nature of light and our sight. How is a rainbow formed?

Activity 8. Allow a very narrow beam of bright light to fall on one face of a prism. Hold a white screen on the other side so that light emerging out of the other face falls on it (Fig. 12.19). You will see that the light has spread out into many colours on the screen. *This splitting up of light into its various components is called* **dispersion.** The spread out patch of light on the screen is called a **spectrum.**

You will observe that the order of colours is the same as that seen in a rainbow. While the seven colours in a rainbow are red, orange, yellow, green, blue, indigo and violet, the major rainbow colours you may be able to detect are red, orange, yellow, green, blue and violet. The deviation is seen to be least for red and most for violet. The refractive index of a transparent material is the maximum for violet and the least for red. Thus, the reason of dispersion is the different deviations of different colours produced due to the difference in refractive indices for them.

Light, which is a mixture of many colours, is called composite light. The combination of all rainbow colours is called *white light*; light from the Sun is white light. (Light itself is invisible; yet the term 'white light' is in common usage. You should therefore clearly understand the meaning of this term.) Is it possible to recombine the colours obtained in the spectrum in the above experiment to obtain 'white light' again.

Activity 9. In the experiment described in Activity 8, remove the screen and place a second prism with base upwards in the path of the dispersed light from the first prism. Make sure that the light emerging out of the first prism falls on a face of the second prism. The white sreeen is placed in the path of the light transmitted through the second prism, which will also need some adjustment. You will obtain on the screen a single beam of undispersed light (Fig.12.20).

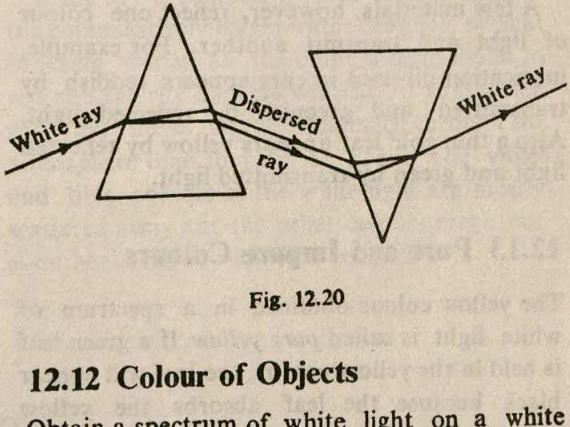


Fig. 12.20

12.12 Colour of Objects

Obtain a spectrum of white light on a white screen in a darkened room. Now hold a piece of red wool in the path of the spectrum so that it is first illuminated by green, and then by red light. The wool appears red in the red light and black in green light. Now examine a piece of blue wool in red and green light; it appears black in both cases. Thus, the *colour of an object* *not only depends upon the nature of its surface material but also on the light that falls on it.*

The colour of an opaque object depends upon the colour of light which it reflects to the eye. When white light falls on an opaque object, a part of it is absorbed by the object and the rest is reflected; the reflected part falls on our eyes and gives the object its characteristic colour. An object is called *red* if it absorbs all other colours except red, which is reflected. *We call an object black if it absorbs all the light that falls on it and an object white if it reflects all the light that it receives.* A coloured object can only *subtract*, not add, light.

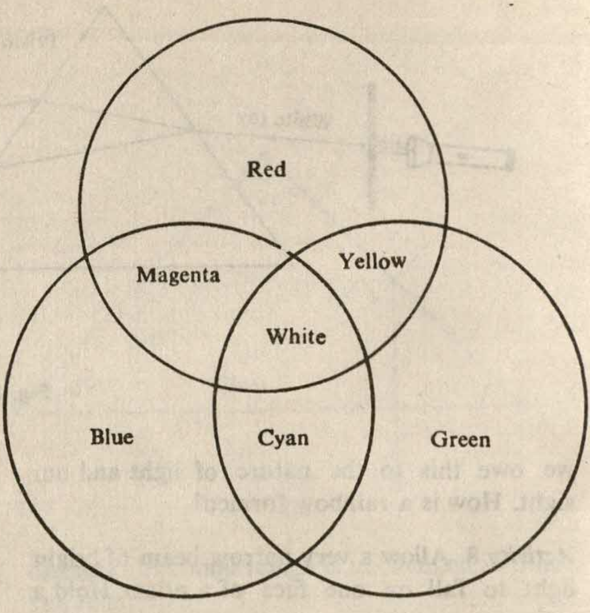
The colour of a transparent object depends upon the colour of light which it reflects or transmits. When white light falls on a transparent object, a part of it may be absorbed and the rest transmitted or reflected. On seeing through the object the transmitted part reaches our eye and gives the object its characteristic colour. On holding a red glass plate in white light and looking through the glass we see that it appears red; the glass plate absorbs all colours except red. Ordinary window glass transmits light of all the colours and appears to be colourless.

A few materials, however, reflect one colour of light and transmit another. For example, lubrication oil used in cars appears reddish by transmitted and greenish by reflected light. Also a thin gold leaf appears yellow by reflected light and green by transmitted light.

12.13 Pure and Impure Colours

The yellow colour obtained in a spectrum of white light is called *pure yellow.* If a green leaf is held in the yellow colour, the leaf will appear black because the leaf absorbs the yellow colour and no light is reflected to the eyes.

Activity 10. Take three projectors or flash lamps and fix in them slides of red, green and blue coloured gelatine sheets. Project the coloured lights on a white screen (Fig. 12.21). You will observe that at the place where the three colours overlap, a white patch is produced. By using two projectors at a time, you can obtain the following colours:



Colours by addition

Fig. 12.21

Red + Blue = Magenta
Blue + Green = Cyan (Peacock blue)
Red + Green = Yellow

The yellow obtained by a combination of red and green is called impure yellow; if a green leaf is illuminated by it the leaf will absorb red and reflect green, and hence will appear to be green.

If the red, green and blue colours in the above experiment are mixed in varying proportions we can obtain innumerable colours including those of the spectrum; red, green and blue are therefore called the *primary colours.* Thus, addition of colours takes place in mixing various components of light.

Colour of Pigments

When pigments are mixed, each pigment subtracts or absorbs certain colours from the incident light; the colour which has not been absorbed is the resulting colour of the mixture.

It is a common experience while painting that when blue and yellow pigments are mixed, the result is green. Blue paint reflects not only blue

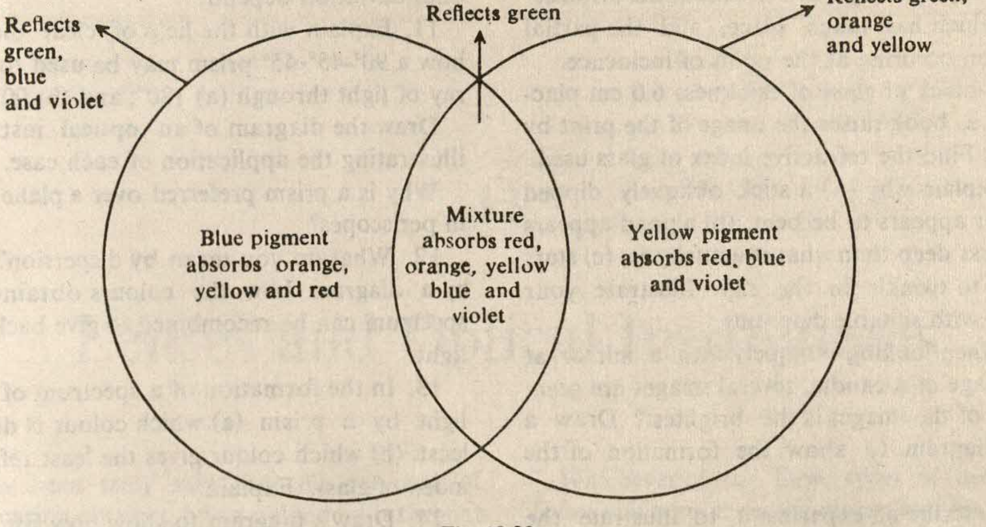

Reflects green, blue and violet
Reflects green
Reflects green, orange and yellow
Blue pigment absorbs orange, yellow and red
Mixture absorbs red, orange, yellow blue and violet
Yellow pigment absorbs red, blue and violet

Fig. 12.22

but also violet and green, and absorbs yellow, orange and red. Yellow paint reflects yellow, green and orange colours but absorbs violet, blue and red. On mixing the two, the only colour from the white light incident on it which is reflected is green; all other colours are absorbed (Fig. 12.22).

On mixing yellow, blue and orange in proper proportions all spectral colours are subtracted from the white light and the mixture appears black. Yellow, magenta and cyan are called primary pigment colours; these are complementary colours of red, green and blue.

Colour of Sky

The blue colour of the sky and the reddish-yellow colour at sunset are based upon the phenomenon of scattering of sunlight. Fine dust particles and air molecules scatter, in all directions, the blue and violet colours much more than the other colours. In whatever direction we look above, violet and blue colours reach our eyes and impart the colour to the sky.

If the sky is overcast by thin Cirrus clouds, the comparatively bigger water droplets present in them scatter all the colours from violet to red and the sky appears whitish. At sunset the sun rays travel a greater distance through the atmosphere than they do at noon. The violet and blue colours of the white light are mostly scattered away and the other colours reach our eyes; hence the sky appears reddish.

QUESTIONS

1. What causes the bending of light from one medium to another? The refractive index of glass is 1.5; what does it mean? Construct the path of a ray of light passing through a glass block when the angle of incidence in air is 30°.

2. Explain the factors on which lateral displacement depends. Under what condition is the lateral displacement zero?

3. Draw a clear ray diagram showing a ray of light incident on a rectangular glass block and emerging from the opposite face. Show on the diagram, the angle of incidence, the re-

fracted ray, the angle of refraction, the displacement which has taken place, and the partial reflection occuring at the point of incidence.

4. A block of glass of thickness 6.0 cm placed on a book raises the image of the print by 2.0 cm. Find the refractive index of glass used.

5. Explain why (a) a stick obliquely dipped in water appears to be bent; (b) a pond appears to be less deep than what it actually is; (c) stars appear to twinkle in the sky. Illustrate your answer with suitable diagrams.

6. When looking obliquely into a mirror at the image of a candle, several images are seen. Which of the images is the brightest? Draw a clear diagram to show the formation of the images.

7. Describe an experiment to illustrate the meaning of the terms (a) total internal reflection and (b) critical angle. Under what conditions does total internal reflection take place?

8. The refractive index of water is 1.34; what will be the critical angle for a ray of light to be totally reflected at a water-air interface? The critical angle for glass to air is 42°; calculate the refractive index of glass. From the above information state when a ray of light can be totally reflected at a glass-water interface. What will be the critical angle in such a condition?

9. Explain why

(a) a ray of light in air incident on a glass block cannot be totally reflected;

(b) a part of the water surface viewed by a diver from under water may act as a mirror;

(c) on a hot day metalled roads appear to be covered with water;

(d) a specially cut diamond sparkles.

Draw clear diagrams to illustrate your answers, wherever possible.

10. With the help of a clear ray diagram show how deviation takes place during refraction in a triangular glass prism. On what factors does deviation depend?

11. Explain with the help of clear diagrams how a 90°-45°-45° prism may be used to turn a ray of light through (a) 180°; and (b) 90°.

Draw the diagram of an optical instrument illustrating the application of each case.

Why is a prism preferred over a plane mirror in periscopes?

12. What do you mean by dispersion? Show by a diagram how the colours obtained in a spectrum can be recombined to give back white light.

13. In the formation of a spectrum of white light by a prism (a) which colour is deviated least; (b) which colour gives the least refractive index of glass. Explain.

14. Draw a diagram to show how you would obtain a spectrum from sunlight using a prism. Name the colours in the correct order. Why do you normally not get a spectrum from a very broad beam of white light refracting through a prism?

15. State and explain how a spectrum of white light will be obtained using a prism when (a) a red filter is introduced between the source and the prism; (b) red and blue filters are placed between the dispersed light and the screen; (c) a green screen is used to receive the spectrum.

16. A blue mark is made on a strip of white paper. What would you expect to see when the paper is moved in the spectrum formed by white light.

17. Explain why (a) a blue opaque object appears black when viewed in yellow light; and (b) yellow and blue pigments give green colour when mixed.

18. Describe an experiment to show that green and red lights when mixed give yellow light.

19. Explain why (a) the sky is blue during the day; (b) the sky in the west is reddish at sunset.

13

Lenses and Optical Instruments

It has been truly said that 80 per cent of information obtained by an individual is through his sense of sight. The eye, an organ of the sense of sight, is the most perfect and highly automatic optical instrument available in the world. To cure defects in eyesight, millions of people use spectacles which are man made lenses. A **lens** *is a transparent medium bounded by two surfaces of which at least one is spherical.* Although there are many different kinds of lenses of different sizes and shapes which are in use, essentially they are of two types : *converging* and *diverging.*

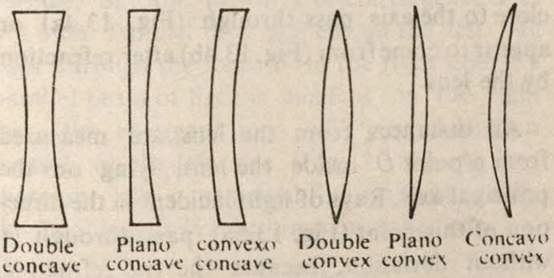
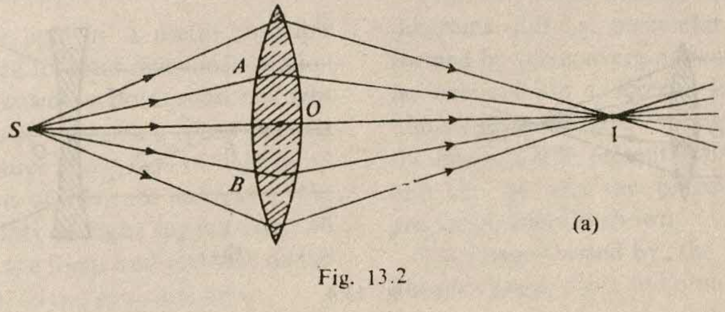


Fig. 13.1

Whichever of the three types of *converging lenses* you take, it can be recognised by the feel of hand; it is thick in the middle and becomes thinner at the edges. The property of a converging lens is to bend the rays of light inwards (converge) as they pass through it. It is also called a *convex lens* because at least one of its surfaces is convex. A *diverging lens* spreads outwards (diverges) an incident beam of light. It is also called a *concave lens* as at least one of its surfaces is concave.

13.1 Lens as a Group of Prisms

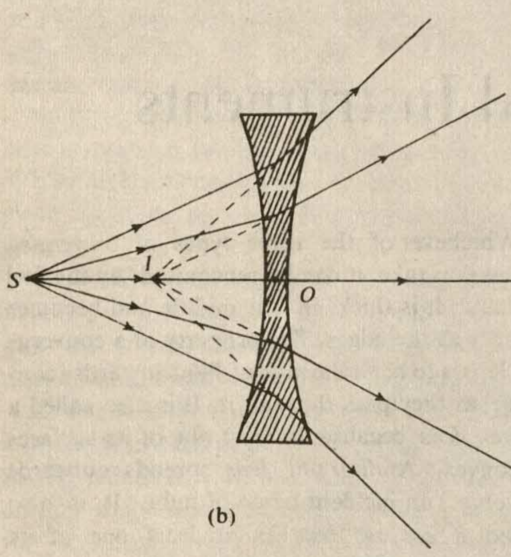
You will remember that a ray of light on passing through a prism bends towards its base and the extent of bending depends upon the angle of the prism. A converging lens can be supposed to be made up of a group of prisms or sections of prisms with a thin glass slab in the middle. The rays of light diverging from a point source *S* fall on the lens. The ray *SO* is transmitted without bending as it is incident normally and



(a)

Fig. 13.2

the two surfaces are parallel. The rays *SA* and *SB*, equidistant from *O*, deviate equally towards the bases of the prism sections and pass through I (Fig. 13.2a). The rays near the edge bend the most and pass through the same point *I*. Thus, the lens converges the rays incident on it from the object source *S* and forms a real image at *I*.



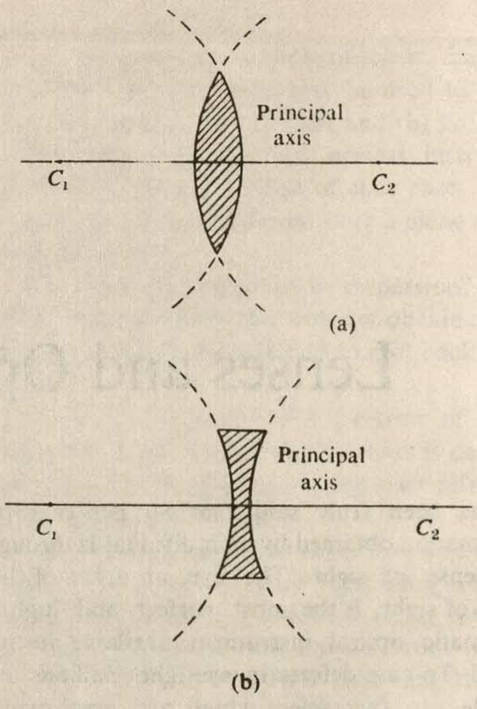
(b)

Fig. 13.2

Fig. 13.2b shows the action of a diverging lens. The rays of light on passing through the lens deviate away from one another. To an observer receiving these rays, the object *S* appears to be at *I*, which is its virtual image.

13.2 Definitions

The **principal axis** of a lens is a line which joins the centre of curvature of the two surfaces of the lens (c_1 and c_2 in Fig. 13.3).



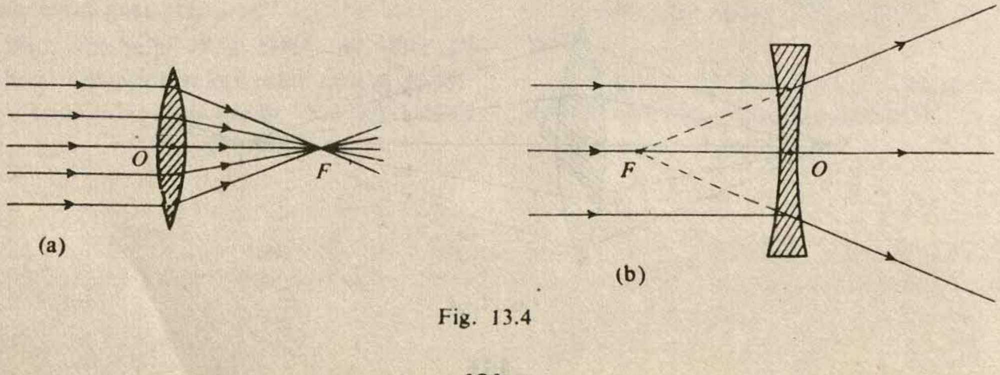
(a)

(b)

Fig. 13.3

The **principal focus**, or simply the focus, of a lens is the point at which the rays of light originally parallel to the axis of the lens and close to the axis pass through (Fig. 13.4a) or appear to come from (Fig. 13.4b) after refraction by the lens.

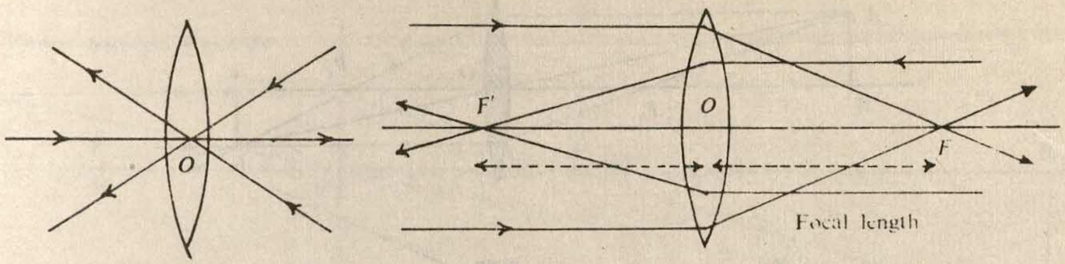
All distances from the lens are measured from a point *O* inside the lens, lying on the principal axis. Rays of light incident in the direction of this point (Fig. 13.5a) pass through it without deviation, because the two refracting



(a)

(b)

Fig. 13.4



(a) (b)

Fig. 13.5

surfaces are parallel. The rays undergo little displacement, because the lens is considered to be very thin. This point is called the **optical centre** of the lens. Hence, the **optical centre** of a lens is a point on the principal axis within the lens through which the rays of light pass without bending.

The distance between the optical centre and the focus of a lens is called the **focal length**. The focal length is positive in a coverging lens as the focus is real and negative in a diverging lens, as the focus in this case is virtual.

Even according to the new cartesian convention the focal length of a converging lens is positive and that of a diverging lens is negative.

Light could be incident on a lens on either surface, but the property of convergence does not alter. Parallel rays incident on the left will pass through the focus *F* on the right side; if a parallel beam of light is incident on the right face, the emergent rays will pass through a focus *F′* on the left side (Fig. 13.5b). A lens therefore has a principal focus on either side; the focal length *f* is the same on either side.

13.3 A Parallel Beam

The reversibility of light is a useful principle which can be applied to determine the formation of ray diagrams. Consider a point source of light placed at the focus of a lens on its principal axis (Fig. 13.6). The source sends rays of light in all directions, and some of them are incident on the lens. The reversibility of light suggests that all rays coming from the focus and incident on the lens will go parallel to the principal axis.

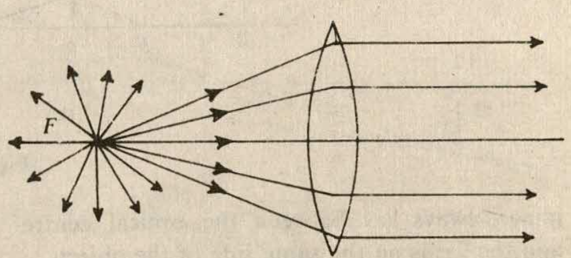


Fig. 13.6

13.4 Ray Diagrams

The image formed by a lens can be located by drawing ray diagrams. Any two rays from a point source and incident on the lens can be taken to obtain the image, but the most convenient rays to take are the following:

(a) A ray parallel to the axis after refraction passes through the focus in the case of a converging lens, or appears to come from the focus in the case of a diverging lens;

(b) A ray passing through the optical centre emerges undeviated;

(c) A ray passing through the focus and incident on the lens after refraction emerges parallel to the principal axis.

Figs. 13.7a and b show the formation of ray diagrams for a particular case. The image formed by the converging lens is real and can be obtained on a screen. It is inverted and diminished in size. If the screen is taken away, the image is still present 'suspended' in space and can be seen by placing the eye in the proper position as shown.

The image formed by the diverging lens is always virtual, erect and diminished in size. The

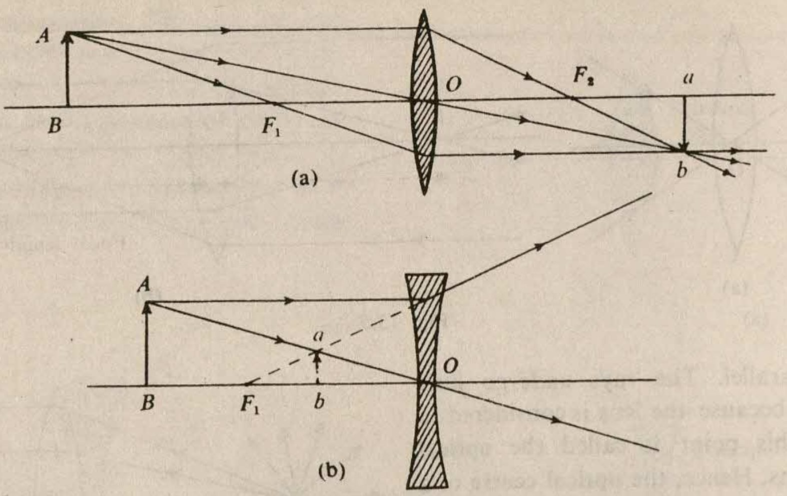


Fig. 13.7

image always lies between the optical centre and the focus on the same side of the object.

13.5 Images Formed by a Converging Lens

The images formed by a converging lens vary in size, location and nature according to the position of the object. Scale diagrams can be drawn by selecting suitable scales and drawing rays which are most convenient.

(a) When the object is between the focus and the lens, the image is virtual, erect and magnified. It is formed on the same side as the object. This position is used in the case of a magnifying glass (Fig. 13.8a).

(b) When an object is at the focus, no image is formed since the refracted rays from a point source of object emerge parallel to each other (Fig. 13.8b). A lens in this position is used as the 'eye piece' in a telescope to obtain a parallel beam.

(c) When an object is between *F* and 2*F*, its real, inverted and magnified image is

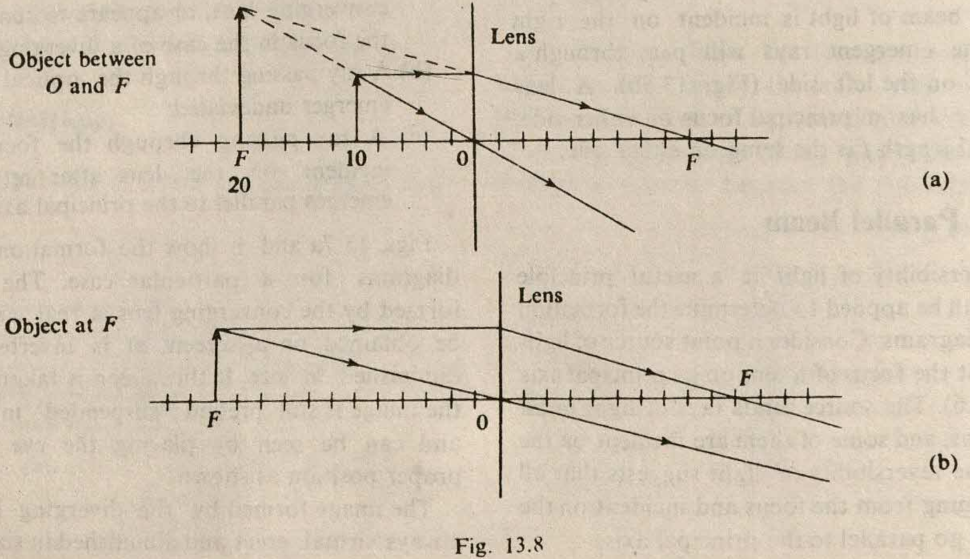


Fig. 13.8

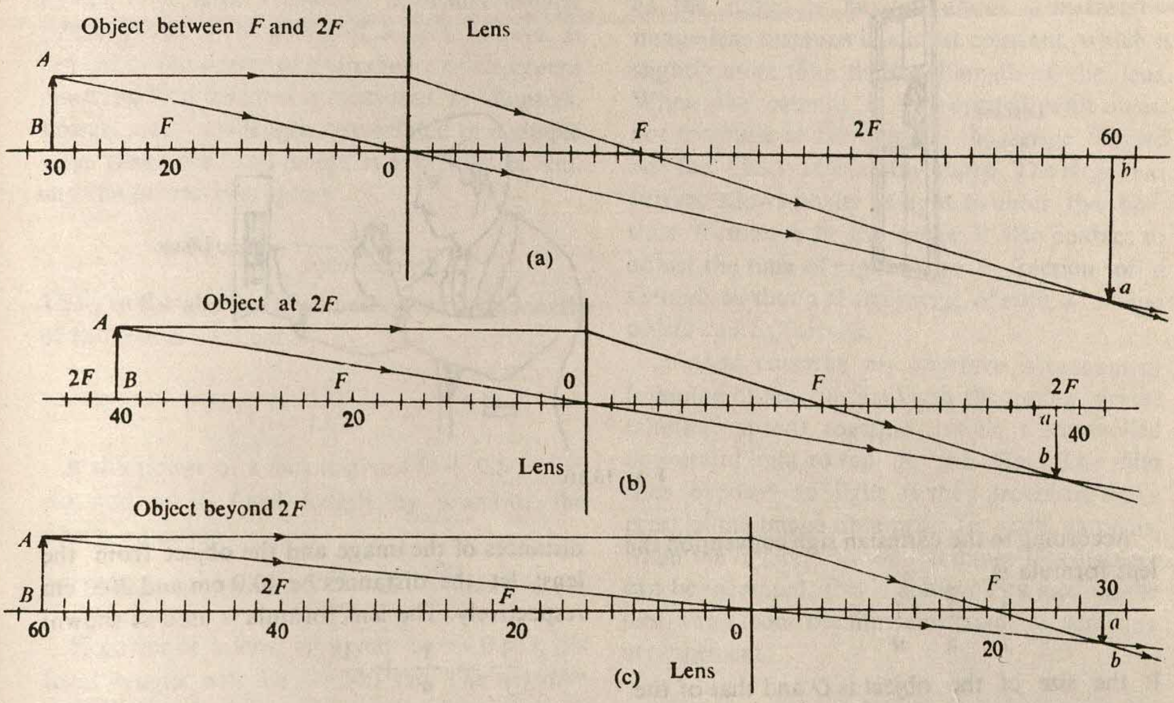


Fig. 13.9

formed at more than $2F$ distance away from the lens (Fig. 13.9a). The 'projection lens' of a slide or movie projector is adjusted in this position.

(d) When an object is at twice the focal length distance from the lens, its real, inverted and same size image is obtained at the same distance on the other side of the lens. The shortest object-to-image distance, $4f$, is obtained in this condition (Fig. 13.9b).

(e) When an object is more than $2f$ distance away from a converging lens, its real, inverted and diminished image is obtained between F and $2F$ on the other side of the lens (Fig. 13.9c). A camera uses a lens in this situation to form an image on the film.

13.6 Image of a Distant Object

Activity 1. Stand inside a room and arrange a white sheet of paper to face a distant object such as a tree or a window. Hold a convex lens in between and adjust its position to obtain a clear image of the tree or window on the sheet. You will obtain an inverted image on the sheet; the image has been formed by the rays actually incident on the screen and is *real*. A real image formed by one lens is always inverted (Fig.13.10).

Measure the lens to image distance. You will realise that this distance is almost equal to (perhaps slightly more than) the focal length of the lens. For all practical purposes, therefore, we assume that rays incident on the lens from an object a few metres or more away are very nearly parallel; hence, the focus and image coincide when the object is very far away.

13.7 Lens Formula

As in the case of mirrors, a simple mathematical relationship exists between object distance u, image distance v and the focal length f of the lens. Observing the old convention of signs in which real distances are positive and virtual distances are negative we have

$$\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$$

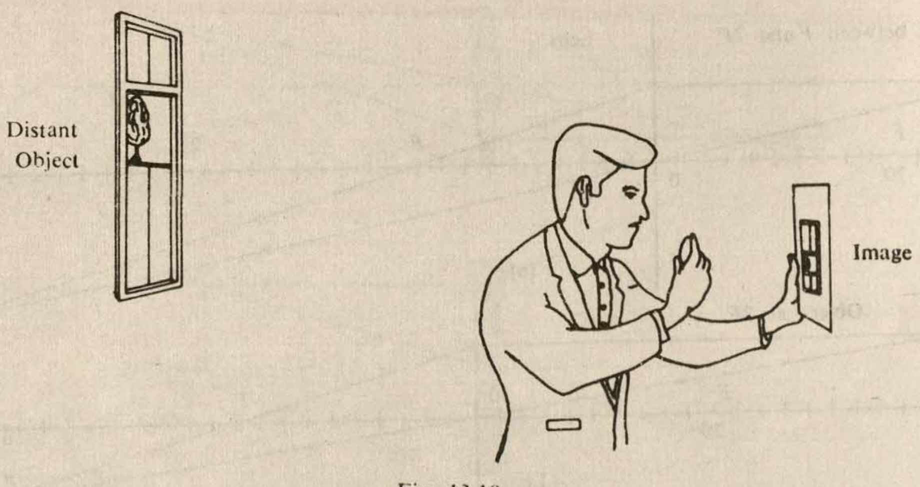


Fig. 13.10

According to the cartesian sign convention the lens formula is

$$\frac{1}{f}=\frac{1}{v}-\frac{1}{u}$$

If the size of the object is O and that of the image I, then the magnification m is given by

$$m=\frac{I}{O}=\frac{v}{u}$$

The magnification m is positive if the image is real and is negative when the image is virtual.

13.8 Focal Length of a Converging Lens

Activity 2. Place a lighted candle in front of the lens at a distance more than the rough focal length as determined in Activity 1. If the value obtained is 15 cm, hold the candle 20 cm away from the lens. Place a screen on the other side of the lens and move it gradually away from the lens until a sharp image of the candle is obtained on the screen. The image will be inverted and magnified (Fig. 13.11). Measure the distances of the image and the object from the lens; let the distances be 40.0 cm and 20.0 cm respectively. The lens formula is used as shown:

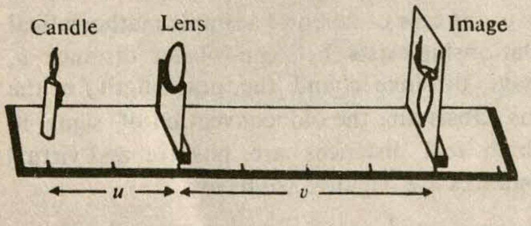


Fig. 13.11

$$\frac{1}{f}=\frac{1}{u}+\frac{1}{v}$$

$$=\frac{1}{20}+\frac{1}{40}=\frac{2+1}{40}=\frac{3}{40}$$

Hence $f=13.3$ cm

According to the new cartesian sign convention

$u=-20$ cm

$v=+40$ cm

$$\therefore\ \frac{1}{f}=\frac{1}{v}-\frac{1}{u}=\frac{1}{40}-\left(-\frac{1}{20}\right)$$

$$=\frac{1}{40}+\frac{1}{20}=\frac{3}{40}$$

$$f=\frac{40}{3}=13.3\text{ cm}$$

Also, Magnification

$$m=\frac{v}{u}=\frac{40}{20}=2$$

Now change the object distance u in steps of about 5 cm and find out the corresponding image distance v; hence, calculate the value of focal length. The value of f is found to be almost constant within the limitations of experimental error.

13.9 Power of a Lens

Focal length is an important physical characteristic of a lens. However, opticians usually talk in terms of the **power** of a lens. *Power is defined as the degree of convergence or divergence produced by a lens and is measured in* **dioptres**. Power and focal length are related in a simple way. When the focal length is expressed in cm, and the power in dioptre:

$$\text{Power} = \frac{100}{\text{focal length}}$$

Thus, in the above experiment when focal length of the lens is 13.3 cm,

$$\text{Power} = \frac{100}{13.3} = +\ 7.5\ \text{D}$$

If the power of a lens is given as + 0.5 D, we can find out its focal length by rewriting the above equation:

$$\text{Focal length} = \frac{100}{\text{power}} = \frac{100}{0.5} = 200\ \text{cm}$$

If power of a lens is given as − 0.5D, its focal length will be − 200 cm. The negative sign indicates that it is a diverging lens. A diverging lens has a negative power and a negative focal length.

13.10 Lens Camera

The box camera is similar in construction to a pin hole camera except that there is a converging lens instead of the hole and the screen is a light-sensitive film. When the shutter *S* is opened, light from a distant object passes through the lens and forms a real, inverted and diminished image on the film *E* (Fig. 13.12). As long as the object is beyond about 4 metres, the image-lens distance is almost constant, which is slightly more than the focal length of the lens. When the camera is so adjusted, with object not too close to the camera, the image formed on the film is reasonably sharp. The large lens surface allows plenty of light to enter the box, thus forming a bright image; it also enables to adjust the time of exposure to a fraction of a second so that a sharp image of even a moving object can be formed.

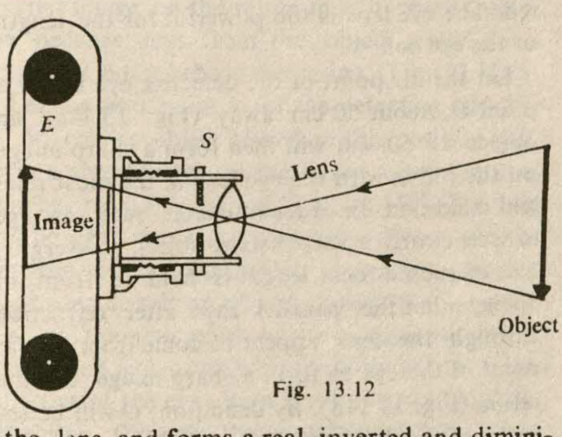


Fig. 13.12

In good cameras an aperture arrangement (opening of lens surface) and the timing device (shutter speed) together enable a controlled amount of light to fall on the film. The film thus exposed to light is then processed and a print of the image obtained. In such cameras, when the object is closer, the image-lens distance can be increased; this is achieved by moving the lens away from the film, employing a screwing arrangement.

13.11 The Eye

The eye resembles a lens camera in many ways but there are some important differences also. In its action and performance, the eye is a highly perfect automatic optical instrument.

Its lens is made of a jelly-like material; it converges light to form a real, inverted and diminished image of an object on the light-sensitive screen called **retina** (Fig. 13.13). The **optic nerve** carries the impressions on the retina to the brain where it is made erect and interpreted.

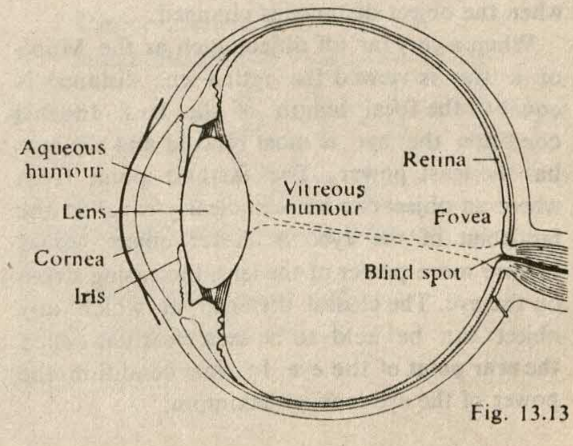


Fig. 13.13

The coloured circular portion in front of the eye lens is called the **iris**; by muscular action it adjusts the aperture of the lens, thus controlling the amount of light entering the eye. The central opening through which light enters the eye is called the **pupil**; from outside, it appears black.

Activity 3. Hold a mirror in front of you and look into your eyes. Locate the iris and the pupil in the middle of it. Now shine a torch in one of the eye balls and notice how the pupil's width changes. You will observe that the pupil area becomes smaller and reduces the amount of light entering the eye; this is essential to avoid damage to the retina. Now remove the torch and observe the increase in the size of the pupil. This action of the iris in adjusting the aperture is almost automatic (involuntary).

An important difference between a camera and an eye is the arrangement for obtaining a clear image on the screen. In a camera, when the object comes closer, the image-lens distance is increased; hence, the lens has to be moved forward to bring the image on the film. When a closer object is to be clearly seen by the eye, the eye lens power increases, thus effectively keeping the image-lens distance constant. Power of the eye lens is changed by making the lens thick (more power) or thin (less power); this is accomplished by the stretching or relaxing of the **ciliary** muscles. This involuntary action of the ciliary muscles is called the **accommodation of the eye**. It suitably alters the power of the eye lens to obtain a sharp image on the retina when the object distance is changed.

When a very far off object such as the Moon or a star is viewed the retina-lens distance is equal to the focal length of the lens. In this condition the eye is most relaxed and the lens has the least power. The farthest point from where an object can be seen clearly is called the **far point** of the eye. A closer object would require more power of the lens, increasing strain on the eye. The closest distance at which any object can be held to be seen clearly is called the **near point** of the eye. In this condition the power of the eye lens is maximum.

Activity 4. Hold this book in front of you and look at the words. Move the book closer to your eyes; keep your eyes fixed on the words. You will find that the eye will have to be strained more and more to see the words clearly. Finally, at a certain point the words start looking blurred. Now gradually take the book away from your eyes and stop when you see the words clearly again. Measure the distance of the book from the eyes; this is the near point distance for your eye. For normal eye sight, the near point distance is about 20 to 25 cm; children have a closer near point. This distance is called the **least distance of distinct vision.**

13.12 Defects of Vision

We see a lot of people around us wearing spectacles; some wear coloured glasses, whereas others wear them to correct defects of vision. Let us consider the cause of some defects and how spectacle lenses are used to correct them.

Myopia or Short Sight is a defect of the eye when distant objects cannot be seen clearly; this is caused when the eye ball is elongated so that the retina-lens distance is increased. For the normal eye, an object at great distance forms a clear image on the retina. We can say that its far point is at infinity (Fig. 13.14a). The same object will form a sharp image between the eye lens and retina in a myopic eye (Fig. 13.14b). The image on the retina will therefore be blurred. The eye lens is too powerful for the length of the eye ball.

Let the far point of the defective eye be at a point O, about 50 cm away (Fig. 13.14c); an object at 50 cm will then form a sharp image on the retina with the eye lens in the most relaxed condition. In order to enable such an eye to see clearly a very distant object, a diverging lens of such a focal length is held in front of the eye that the parallel rays after refraction through the lens appear to come from the far point of the eye to form a sharp image on the retina (Fig. 13.14d). By definition, O will be the focus of the diverging lens, and its power will be $- 100/50 = - 2$ Dioptre.

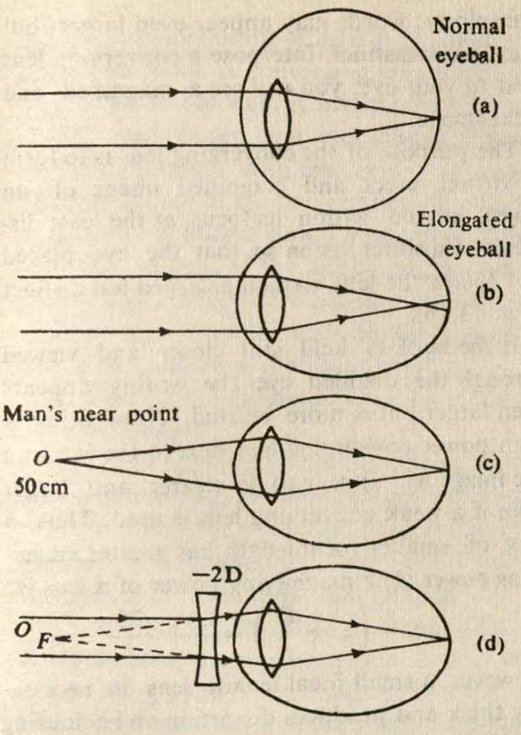


Fig. 13.14 Myopic eye

Hypermetropia or Long Sight is a defect of the eye when near objects cannot be seen clearly; it is caused by shortening of the eye ball so that the retina-lens distance becomes smaller. For the normal eye, an object at near point *N*, situated at 25 cm, forms a clear image on the retina when the eye lens has maximum power (Fig. 13.15a). The same object will form a blurred image on the retina in a hypermetropic eye because rays from the object would converge to a point behind the retina (Fig. 13.15b).

Let the near point *n* for the defective eye be at 50 cm; an object placed in this position will form a sharp image on the retina when the eye lens has maximum power (Fig. 13.15c). The eye will be able to clearly see any object placed between 50 cm and infinity. To enable such an eye to see clearly an object placed 25 cm away (i.e. at the near point of the normal eye *N*), a converging lens of suitable focal length is held in front of the eye. Rays from the object, after refraction through the converging lens will appear to come from the image which will be at 50 cm (i.e. near point of the defective eye *n*) as shown in Fig. 13.15d.

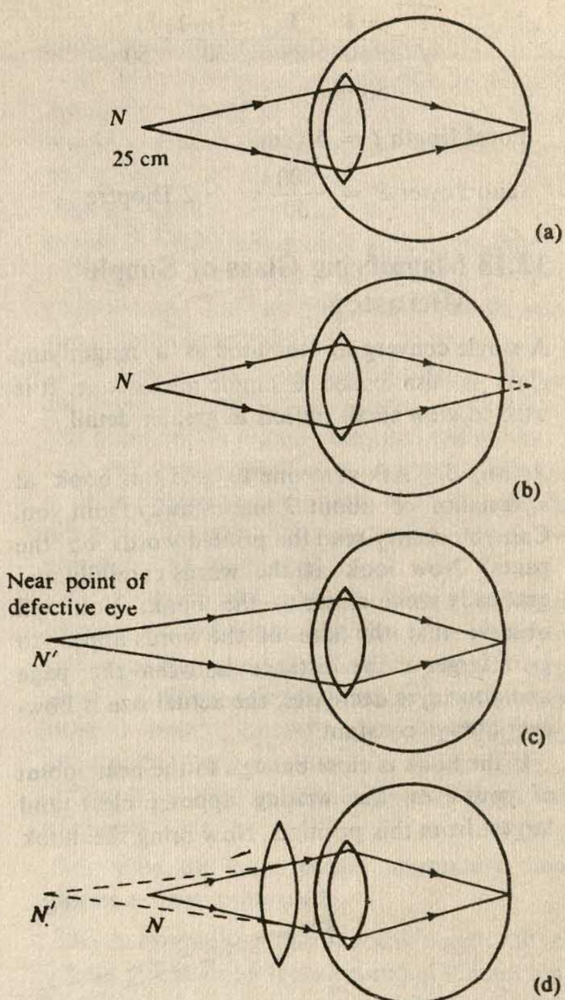


Fig. 13.15

Object distance $= D = 25$ cm

Image distance $= -d = -50$ cm

Hence,
$$\frac{1}{f} = \frac{1}{D} + \frac{1}{d} = \frac{1}{25} - \frac{1}{50}$$
$$= \frac{2-1}{50} = \frac{1}{50}$$

According to the new cartesian sign convention

Object distance $u = -25$ cm

Image distance $v = -50$ cm

As
$$\frac{1}{f} = \frac{1}{v} - \frac{1}{u}$$

$$\therefore \quad \frac{1}{f}=\frac{-1}{50}+\frac{1}{25}=\frac{-1+2}{50}=\frac{1}{50}$$

$$\therefore \quad f=50 \text{ cm}$$

Focal length $f = 50$ cm

and Power $P = \frac{100}{50} = +2$ Dioptre

13.13 Magnifying Glass or Simple Microscope

A single converging lens used as a magnifying glass is also called a simple microscope. It is used to view small objects in greater detail.

Activity 5. Ask someone to hold this book at a distance of about 3 metres away from you. Can you clearly read the printed words on the pages? Now look at the words carefully and gradually move closer to the book. You will observe that the size of the words appear to grow larger as the distance between the page and your eyes decreases; the actual size is however always constant.

If the book is close enough to the near point of your eyes; the writing appears clear and largest from this position. Now bring the book even closer; words may appear even larger but they are indistinct. Interpose a converging lens next to your eye; you will see a magnified and clear image.

The purpose of the converging lens is to form a virtual, erect and magnified image of an object placed within its focus, at the least distance of distinct vision so that the eye placed *just behind* the lens views it enlarged but distinct (Fig. 13.16).

If the book is held still closer and viewed through the unaided eye the writing appears even larger but is more blurred. Now bring a high power converging lens next to the eye, and the image will appear to be clearer and larger than if a weak converging lens is used. Thus, a lens of smaller focal length has greater **magnifying power**. The magnifying power of a lens is

$$m = \left(1+\frac{D}{f}\right) = 1+\frac{25}{f}$$

However, a small focal length lens is necessarily thick and produces distortion and colouring of the image near the edges. In good instruments where greater magnification without distortion and dispersion is required, two lenses arranged in a special way are used.

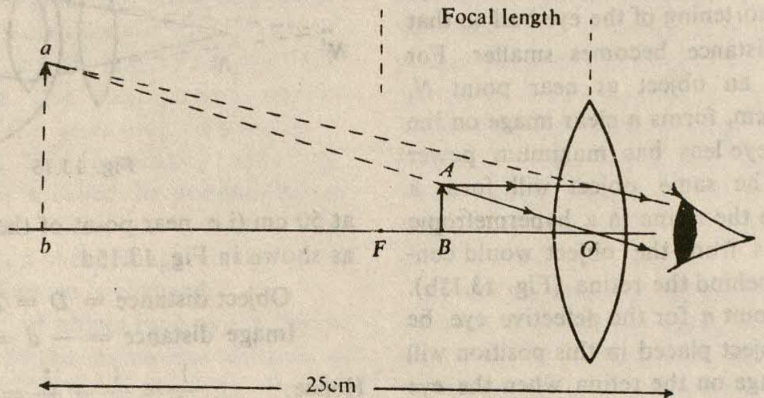


Fig. 13.16

QUESTIONS

1. What are the main differences between a diverging and a converging lens (a) in their construction, (b) in their properties? Illustrate your answer with diagrams.

2. Explain the terms focus, principal axis and optical centre as applied to a converging lens. Describe one method of determining the focal length of this lens.

3. A parallel beam of light is incident on a wall in a room. A converging lens is held in its path close to the wall. A bright circular patch of light surrounded by a dark ring is formed on the wall. Explain with the help of a diagram the appearance of the two sections thus formed. If the lens is moved slowly away from the wall, how will the sizes of the bright patch and the dark ring be affected? What sort of appearance will you obtain on the wall if the converging lens is replaced by a divergent lens?

4. What is the difference between a real and a virtual image?

With the help of clear diagrams, explain how a converging lens can produce an image of approximately twice the size of an object in two different positions of the object. What are the differences between these two images?

5. An object 5 cm tall is placed at a distance of 40 cm from a converging lens of focal length 16 cm. By graphical construction find the position, size and nature of the image. Also calculate the magnification of the image.

6. What is meant by power of a lens? Define a dioptre. If the focal length of a converging lens is 30 cm, calculate its power. What would be the focal length of a lens whose power is $-4D$? What type of lens is it?

7. A box camera forms a clear image on the film when the object is 4 m away. How can any external aid help to obtain a clear image of the object held 2 m away from the camera lens? Draw a diagram to explain your answer.

8. State two similarities between the camera and the human eye. What are the limitations of a box camera? Is there any near point of a box camera or a good quality camera?

9. Draw a simple and labelled diagram of the human eye. Compare the action of the human eye to that of a lens camera with regard to (a) the method of 'focussing' near and distant objects, (b) the method of controlling the amount of light which enters the instrument.

10. What is myopia (short sight)? What causes it and how can it be corrected? Illustrate your answer with diagrams.

11. What happens to a parallel beam of light as it passes into a short-sighted eye? How can the beam be brought to focus on the retina?

12. What is meant by near point? How does a long-sighted person view an object unaided when it is placed at the near point. How can this defect be corrected?

13. Consider the case of a human eye which cannot accommodate, and can focus clearly on the retina the image of an object placed 1 metre away. (a) What type of spectacle lens should be used to view a distant object? (b) Which lens should be used to view an object held at 25 cm from the eye? Explain your answer with diagrams.

14. Why do most people eventually wear glasses as they grow old?

15. A magnifying lens of focal length 20 cm is held 10 cm away from an object 0.5 cm long. By graphical construction find the nature, size and position of the image. If the lens is moved nearer the object, will the magnification increase or decrease?

16. Calculate the magnifying power of a convex lens of focal length 5 cm?

14

Energy and Wave Motion

An important aspect of energy is the mode by which it can be carried from one place to another. There are three modes of transmission of energy. Firstly it can be carried from one place to another by 'moving objects', such as a bullet in flight; secondly it can be handed over from particle to particle as is the case in the transmission of heat energy by conduction. There is a third mode—transfer of energy by wave motion—which may not involve any matter during the transit.

We are surrounded by waves, some of which are visible and some invisible. The ocean in its fury sends gigantic waves to the shore and may cause death and destruction; the energy conveyed by them is sufficient enough to erode the shore line and uproot trees. This is an example of waves on the surface of water. The jet planes zooming high above in the sky send such energetic sonic booms that they may even shatter window panes and produce a deafening noise; this is an example of transmission of energy by sound waves. We can tune to almost any radio station and listen to music or news reaching us through space from thousands of kilometres away; this is an example of radio wave propagation.

14.1 What is a Wave?

Every one of you at one time or another may have thrown a pebble into a quiet pond and

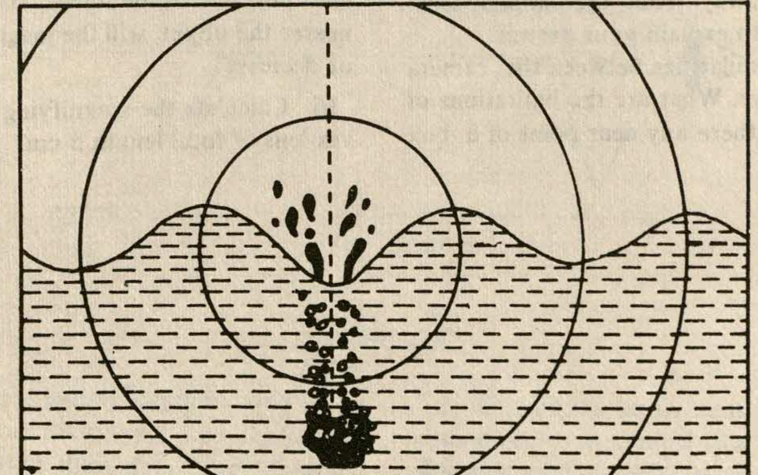


Fig. 14.1

watched circular ripples spread out from the spot where the pebble hit the water surface. If a small bit of wood or a paper boat is made to float on the pond, then on throwing a pebble you would probably notice that the piece of wood moves up and down as the ripple passes outward (Fig. 14.1); it does not travel along with the ripple. The piece is vibrating while the ripple is passing through the point, but once the ripple or disturbance has passed, every particle of water is left where it was. *Such a disturbance produced in a medium by the to and fro motion of its particles is called a* **wave.**

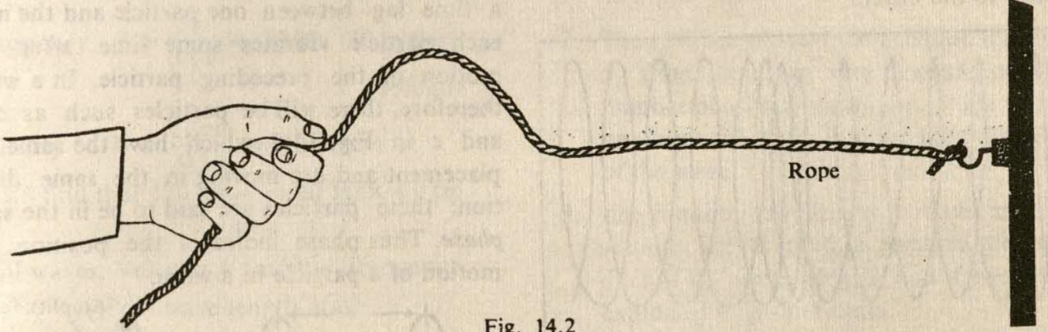


Fig. 14.2

14.2 Wave as a Carrier of Energy

In the example of water waves in a pond the energy conveyed by dropping a stone in water travelled outward so that a stationary piece of wood on the surface started vibrating when the wave reached it.

Activity 1. Tie one end of a long rope to a loosely fixed peg in a table or door. By flicking the other end of the rope up and down send a single pulse along it (Fig. 14.2). You will notice that the peg can be pulled out due to the energy from the hand conveyed by the pulse through the rope.

We therefore conclude that wave is a carrier of energy.

14.3 Transverse Wave

Activity 2. Take a long spiral spring called *slinky* and stretch it on a long table between two rigid supports on either ends. Tie a small ribbon about midway on the spring. Displace the spring at one end by quickly pulling it sideways. You will notice that a pulse travels along the spring and also returns after reflection at the other end (Fig. 14.3). The ribbon moves sideways as the pulse passes through that point along the spring.

In order to produce a wave motion, hold one end of the spring in your hand and move it continuously sideways to and fro along the table top; the continuous pulses will produce a wave. Such a wave is called a **transverse wave.** *A transverse wave is the disturbance produced in an elastic medium which travels at right angle to*

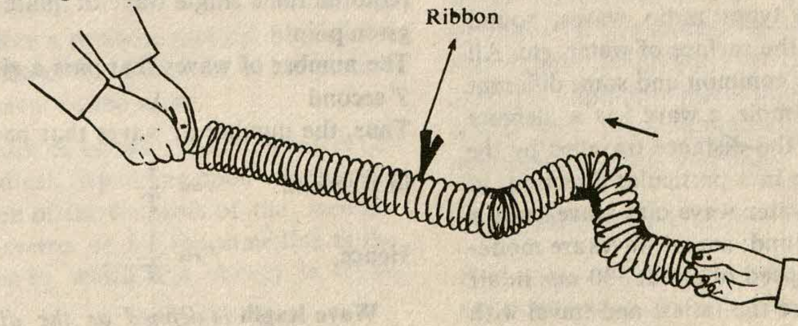


Fig. 14.3

the direction of the periodic motion of the particles of the medium.

14.4 Longitudinal Wave

Activity 3. Compress a few turns of a coil at one end and then release them. A pulse of compression as shown in Fig. 14.4 moves from one end to the other.

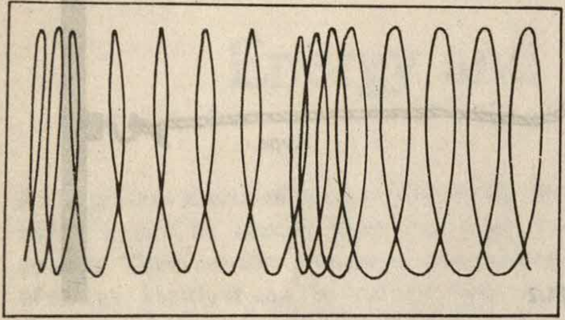


Fig. 14.4

Now stretch apart the coil turns at one end of the spring to form a *rarefaction*. As the coil is released, you will notice that the pulse of rarefaction moves forward from this end to the other. It should be noted that the elements of the spring move backward or forward along the same line as the transit of energy. *When the particles of a medium move in the same direction in which a wave travels, such a wave motion is called* **a longitudinal wave**. Sound waves in gases and liquids are longitudinal in nature.

14.5 Characteristics of Waves

Waves are of many types: radio waves, sound waves, waves on the surface of water, etc. All of them have some common and some different properties. For example, a wave has a definite *velocity* which is the distance travelled by the wave in a unit time in a particular direction in that medium. A water wave may travel only a few metres in a second; sound waves are moderately fast with a speed of about 330 m/s in air while light waves are the fastest and travel with a speed of 3×10^8 m/s. The velocity of a wave changes whenever there is a change of medium; for example, the speed of light reduces to about three-fourth when it goes from air into water, but the speed of sound in water is almost five times that in air.

As a mechanical wave travels through a medium, the particles of the medium vibrate about their mean positions. There is, however, a time lag between one particle and the next; each particle vibrates some time after the motion of the preceding particle. In a wave, therefore, there will be particles such as *a*, *b* and *c* in Fig. 14.5 which have the same displacement and are moving in the same direction; these particles are said to be in the same *phase*. Thus phase indicates the position and motion of a particle in a wave.

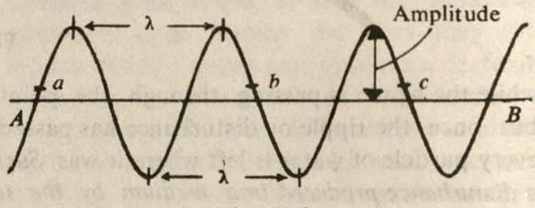


Fig. 14.5

The height of the *crest* or the depth of the trough from the mean position is called *amplitude*. Thus, *amplitude is the maximum displacement of a particle from its rest position in a wave.*

Other important characteristics of a wave are its frequency, time period and wave length. *The frequency f is equal to the number of single waves that pass a given point in a unit time.* It is measured in the unit *hertz* (Hz) or cycles/second.

The *time period T* of a wave is the time required for a single wave or pulse to pass a given point.

The number of waves that pass a given point in T second $= 1$

Thus, the number of waves that pass the point in 1 second $= \frac{1}{T}$

Hence, $f = \frac{1}{T}$

Wave length *is defined as the distance from any point in a wave to the next point in the* *same phase; it is the distance covered by one wave.* It is measured in metres.

Consider the example of a wave which travels from A to B (Fig. 14.5) in 0.1 second. The distance AB is 12 cm and there are 3 single waves in this distance. Then

$$\text{Wave length} = \frac{12\text{ cm}}{3} = 4.0\text{ cm}$$

$$\text{Frequency } f = \frac{3}{0.1\text{ s}} = 30\text{ Hz (30 cycles/second)}$$

$$\text{Velocity } V = \frac{12\text{ cm}}{0.1\text{ s}} = 120\text{ cm/s}$$

We also find that 120 cm/s = 30 Hz × 4.0 cm

or $V = f\lambda$

For all waves, Velocity V (m/s) = frequency f(Hz) × wave length λ(m)

The equation relating velocity, wave length and frequency is true for all types of waves. For example, radio waves have a velocity of 3×10^8 m/s; if a wave has frequency 600 kHz, the wave length will be calculated as follows:

$$\text{Velocity } V = 3 \times 10^8\text{ m/s}$$

$$\text{Frequency } f = 600\text{ kHz} = 6 \times 10^5\text{ Hz}$$

$$\text{Hence, Wavelength} = \frac{\text{velocity}}{\text{frequency}} = \frac{3 \times 10^8\text{ m/s}}{6 \times 10^5\text{ Hz}} = 500\text{ m}$$

To sum up, the following characteristics of wave motion are observed in mechanical waves:

1. A wave motion is energy in transit started by a source producing displacement in the medium.
2. Each element in the wave vibrates, or undergoes a periodic motion, but follows some time after the motion of the preceding element in the wave.
3. Waves can be of two types: transverse or longitudinal, depending upon whether the vibration of the elements of the medium is transverse or in the same line as the direction in which the energy is transmitted.
4. Elements, or particles, which have the same displacement in the same direction are said to be in the same phase.
5. Two successive particles in the same phase are separated by a distance called the wavelength of the wave.
6. The maximum displacement of a vibrating particle from the rest position is called its amplitude.
7. The number of waves which pass through a given point in one second, or the number of vibrations of the source which produces the wave, is called the frequency of the wave.
8. The distance travelled by a wave in one second, i.e. its speed, is equal to the product of its wave length and frequency, expressed in proper units.

14.6 Electromagnetic Waves

As against the mechanical waves which require a medium to travel, the electromagnetic waves do not need any medium although they are transmitted in various material mediums as well. The most common example of an electromagnetic wave is *light*. We receive light energy from the Sun continuously and in great quantity. It is estimated that in the tropical parts of the world about half of the energy received per $(\text{metre})^2$ on the Earth is in the form of light and if fully utilised would provide sufficient energy for one person. This light travels through empty space between the Sun and the Earth with a speed of 3×10^8 m/s. All electromagnetic waves travel with the same speed in vacuum; they are all transverse in nature. Like light, they exhibit the property of getting reflected, absorbed and refracted although the degree to which this takes place depends upon the mediums and their interface.

14.7 Radio Waves

Radio or electric waves form a part of the electromagnetic wave family and are produced by electrons oscillating in conductors.

Activity 4. Take an accumulator and connect two thick copper wires to its two terminals. Place a transistor receiver or radio receiver near the accumulator, and switch on the receiver on the medium wave band where there is no reception from any station. Now touch the two wires momentarily to produce a spark. You will hear a disturbance in the receiver. This shows that during the sparking, radio waves are also produced. Move the receiver away from the battery and try again; the reception becomes fainter as the distance from the source increases. To hear a sound of greater energy, you may try with two or more accumulators in series.

The reception on our radio is due to radio waves transmitted by various stations; these radio waves contain messages in the form of music and speech which a receiver receives and transforms into sound energy to enable us to listen to them.

The electromagnetic waves form a continuous range of radiations spreading from gamma rays (γ-rays) to radio waves (Fig. 14.6). The physical nature of these radiations is the same as far as speed, electromagnetic nature, etc. is concerned; they differ in wave length and frequency. Generally, greater frequency waves have more penetration in any medium. When a wave enters another medium the speed; hence the wave length, changes but the frequency remains unaltered. Frequency is, therefore, a more fundamental property of a wave.

14.8 Infra-Red Radiations

Next to light, the most important radiations received from the Sun are the infra-red, commonly called the heat rays. Objects at a higher temperature radiate infra-red waves of greater frequency than those at lower temperature. When an object is gradually heated, such as an iron bar in a fire, its temperature rises and it gives out infra-red rays. If the temperature becomes as high as about 550°C, the object starts giving out light which is electromagnetic radiation of even shorter wavelength. Higher the temperature, more will be **the**

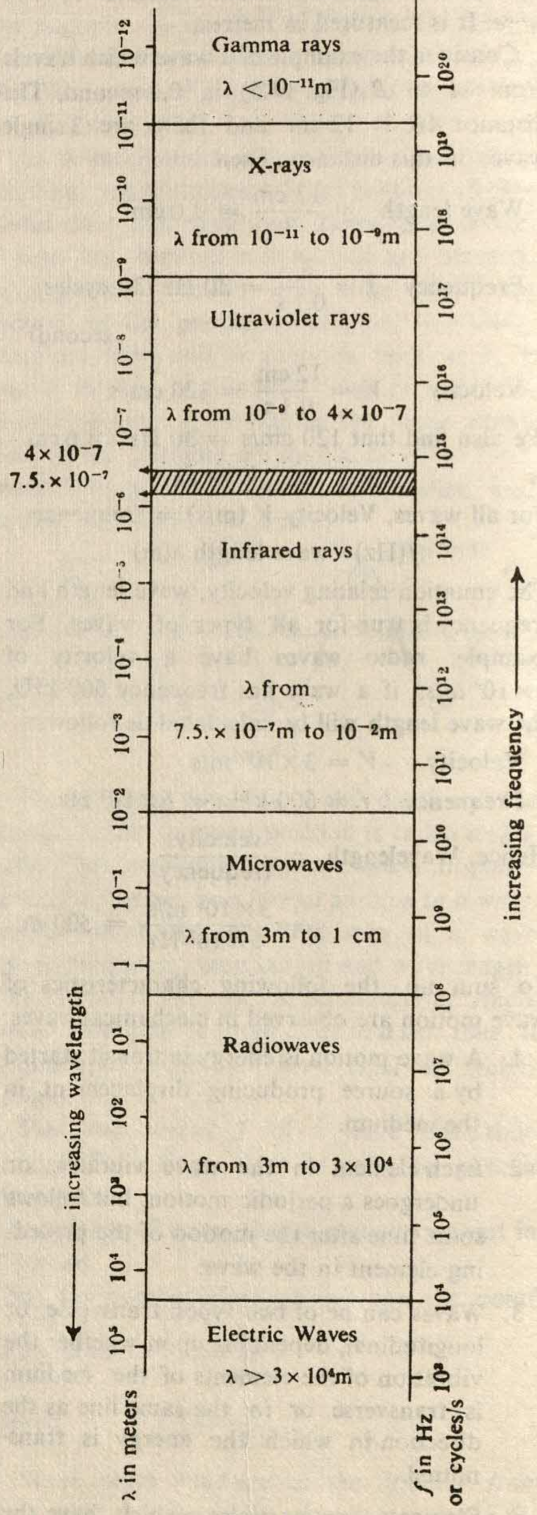


Fig. 14.6

visible light in proportion to infra-red, and the colour of light emitted will also change from dull red to bright red and to yellow. The temperature of objects increases when they absorb the infra-red radiations incident on them.

14.9 Visible Light

Red has a longer wave length than that of yellow, and green light has even shorter wave length. The colour of the light emitted by a heated object gives an indication of its temperature. This is because the frequency of the emitted light is dependent on the temperature of the object. As the temperature increases higher frequencies are emitted. For example, the red hot end of an iron bar will have a lower temperature than the white-yellow filament of a glowing bulb.

The light we receive from the Sun is a mixture of all the spectrum colours which have different frequencies. If the waves of different frequencies strike the retina of the eye separately, they produce an impression of different colours. However, if all these wave lengths fall simultaneously on the retina, as in sunlight, they produce an impression of 'white' light. Light affects photographic plates, although the shorter wave lengths produce greater chemical effect than the longer ones.

14.10 Ultra-Violet Radiations

Ultra-violet have frequency greater than that of visible light. These rays are chemically more active than light; while an excessive exposure to sunlight, in which ultra-violet is present, causes sun burns, they produce vitamin D in the skin. Certain chemicals such as quinine sulphate glow (flouresce) in them. They are present in large quantities in electric arcs and gas discharges, such as the radiation given out by tube-lights.

14.11 X-Rays

Taking X-ray photographs to find out about bone fracture, tooth decay, etc. is a very common occurance. Special X-ray tubes produce these radiations which have frequencies exceeding those of ultra-violet. They penetrate through flesh, cloth and paper but bones are partially opaque to them. The high penetration and energy of these rays could damage living cells in the body; proper precaution has therefore to be taken to protect against over-exposure. The Sun gives X-rays in small quantity and these are mostly absorbed by the atmosphere of the Earth, which is a fortunate thing for us. Other stars also give out X-rays, and one of the scientific purpose of the Indian satellite Aryabhatta was to investigate such sources.

14.12 γ-Rays

The most energetic radiations in the electromagnetic wave family are the γ-radiations. Radioactive materials are the sources of these radiations and an exposure to these may lead to cancer. Nuclear reactors, such as at Tarapore, use such radioactive materials as fuel and very great care is taken to avoid exposure. Atomic and other nuclear bombs release large-scale γ-radiations.

QUESTIONS

1. In which ways can energy be transferred from one place to another? Give examples in each case.

2. Distinguish between transverse and longitudinal waves. Give examples in each case.

3. Define wavelength, frequency and speed of a wave. Illustrate with a diagram and derive a relationship between these quantites.

4. Calculate the wave length in air of a sound note of frequency 256 Hz, when the velocity of sound in air is 330 m/s.

5. Fig. 14.7 shows the side view of water waves in a glass-walled tank. On dropping a pebble into the water, the disturbance at *A* reaches *B* in 2 seconds.

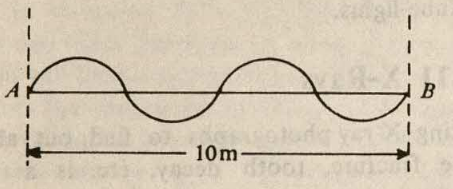


Fig. 14.7

(a) Is there any flow of water in the direction of the wave? How are the particles of water moving? What type of wave motion is this?

(b) What is the wavelength, frequency and velocity in the above case?

6. Mention essential similarities and differences between light and infra-red waves?

7. Radio telescopes receive radio waves from distant sources in space. If a wave has a wave length of 21 cm and travels with the same speed as light, calculate its frequency.

8. The frequency range of ordinary radio broadcasting is from about 540 kHz to 1600 kHz. What is the range of wave length?

9. In an experiment conducted some years ago, radio waves were reflected from the Moon's surface back to earth which took about $2\frac{1}{2}$ seconds. Calculate the distance of the Moon from the Earth.

10. Distinguish between sound and light waves.

15

Sound Waves

We feel thrilled listening to an exponent of music play on his sitar or sarod, but get irritated at the rattling of windows due to sonic booms or thunder of clouds. Loudspeakers and vehicles make us unpleasantly aware of sound in cities while the chirping of birds and murmur of a stream in a forest or a mountain soothen our nerves and give joy to us. The questions that arise are: how is sound produced and how does it reach our ears? What makes a sound unpleasant or melodious?

15.1 What is Sound?

An age old riddle asks: If a tree falls in the centre of a deep forest, where there are no ears to hear it, was there a sound? 'No', says one person, 'If there is no ear to hear it there is no sound'. 'Yes', says another person, 'The sound isn't just the hearing of it. Sound is a thing in itself'. In order to answer the riddle we must define sound. **Sound** *is a series of disturbances or waves in matter to which the human ear is sensitive.* There are three requirements for sound: a source of sound (a vibrating body), a medium to transmit sound waves, and an ear to receive the sound to check whether it is sensitive to the ear or not.

15.2 Source of Sound

Place your finger lightly on the larynx (front part of the throat) when you are speaking, or on a ringing bell. You will feel that the vocal chord or the metal of the bell is vibrating, that is, moving to and fro very fast.

Take a *tuning fork T*. It has two prongs, *A* and *B* (Fig. 15.1a) which vibrate when the fork is lightly struck against a soft pad such as a rubber bung or the rubber sole of a shoe. Observe the prongs carefully after striking; they appear hazy as if they are vibrating very fast. Feel them by slightly pressing against your teeth. You hear the clatter and feel a strong sensation as if the teeth are being struck repeatedly.

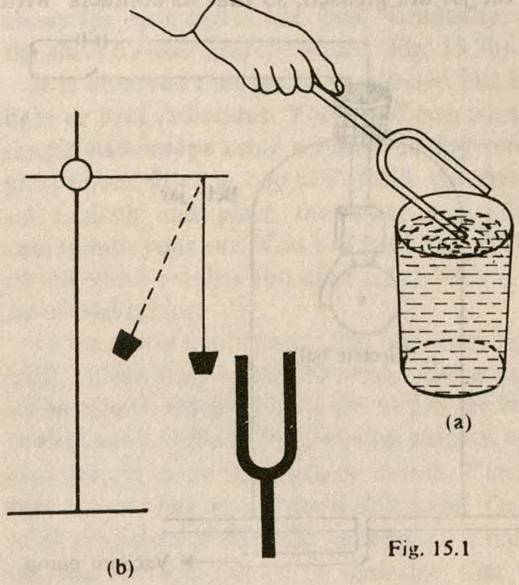


Fig. 15.1

Activity 1. Hold the vibrating tuning fork over water in a wide trough or near a suspended light cork piece. You will see ripples produced on the water surface spreading out from the spot where you touch the prong or you see the cork piece *C* fly away as the prong touches it. Bring the tuning fork near your ear, you will hear the sound.

All these examples show that sound is only produced when a body vibrates. Every sound you hear can be traced back to some vibrating source. It is not essential that the source of sound is a solid. In whistles and flutes, the vibrating air is the source of sound.

15.3 Medium to Travel

Most of the sounds that we hear come to us from a source after travelling through air. What would happen if the air were absent?

Activity 2. Suspend an electric bell inside a bell-jar and place the bell-jar on a platform having a hole in the middle which is connected to a vacuum pump as shown in Fig. 15.2. Edges of the jar are greased, so that its contacts with the platform are air-tight. Connect a battery and a switch in series with the bell and complete the circuit.

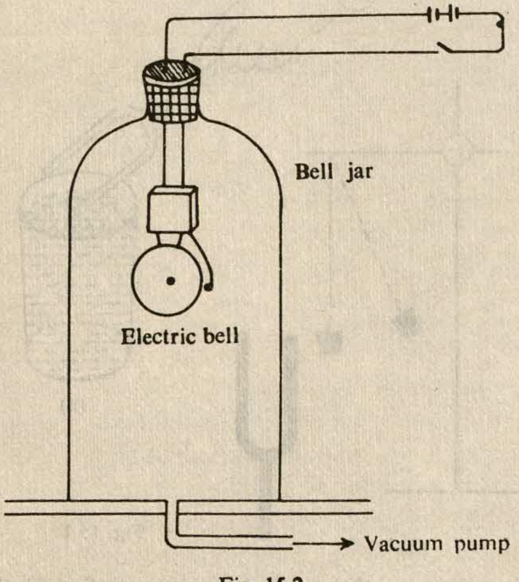


Fig. 15.2

The hammer will be seen striking the gong and ringing of the bell is heard. Now gradually remove air from inside the bell-jar. The sound becomes fainter and fainter, and ultimately dies away. Even when no sound is heard, the hammer is seen striking the gong. Allow the air to enter the bell-jar; the sound is again clearly heard.

Activity 3. Place a watch under your pillow. Its ticks are heard clearly when you lie with one of your ears pressed against the pillow.

Let someone lightly scratch one end of a wooden plank. Its sound is heard only when you press your ear against the other end. These experiments show that sound can travel through air, liquids and solids. In the absence of any medium no sound is heard. It also shows that loudness of sound depends upon the density of the medium through which it travels. The higher the density, louder is the sound.

15.4 Sound Waves

Sound is produced by vibrating objects and it travels in longitudinal waves. Let us see how.

Activity 4. Tightly hold a ruler against the edge of a bench and bend its other end. On releasing it vibrates and produces sound. As the ruler bends forward it pushes the air molecules together making a *compression,* which moves forward (Fig. 15.3a). As the ruler moves backward the air molecules move apart making a *rarefaction* as shown in Fig. 15.3b.

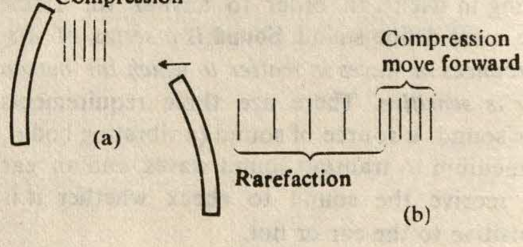


Fig. 15.3

Again when the ruler bends forward, another compression is produced which forces the rare-

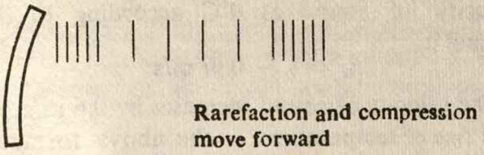


Fig. 15.4

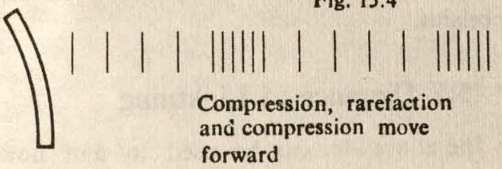


Fig. 15.5

faction and the first compression forwards, see Fig. 15.4. When the ruler bends back again, it makes another rarefaction as shown in Fig. 15.5. In this way a series of compressions and rarefactions are produced and they move outwards from the ruler. This is a sound wave.

The compressions and rarefactions of the sound wave enter the ear and make the thin, taut piece of skin called the *ear drum* vibrate accordingly. This movement of the ear drum is then conveyed to the brain, enabling the sound to be heard and interpreted.

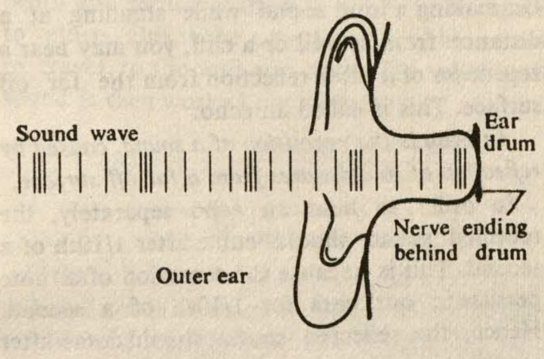


Fig. 15.6

Sound waves are often called *compression waves*. At the time of an earthquake, a series of compression and rarefaction waves move outwards from the epicentre through the rocks of the Earth and cause buildings to move back and forth and eventually collapse. Also the damage which results from an explosion is due to compression waves produced in air.

15.5 Reflection and Absorption

When sound travels in one medium and reaches the surface of another medium, it is either refracted, absorbed or reflected.

Activity 5. Take a box lined with cotton wool. Place a ticking clock into it. Stand slightly away from the box so that the ticking sound is not heard (Fig. 15.7a). Now hold a card sheet above the open end of the box. Gradually tilt the sheet till you hear the sound (Fig. 15.7b).

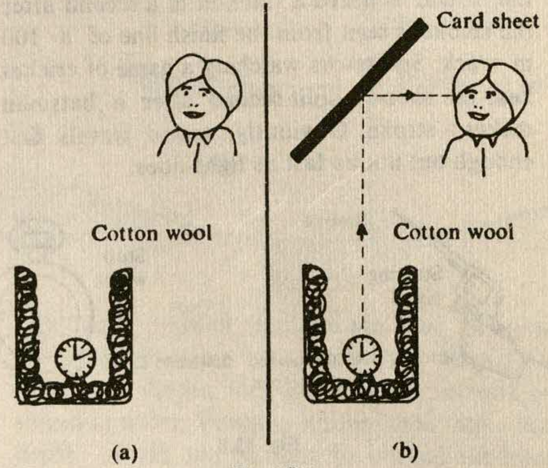


Fig. 15.7

It is observed that sound is reflected just like light or heat radiations. You could construct a simple **stethoscope** using a rubber tubing with a glass funnel fitted at one end. Hold the funnel on a clock and place the other end of the tubing into your ear. You will hear the ticking sound which reaches you after many reflections inside the tubing.

In the above experiment, the box was lined with cotton wool to absorb sound. Good auditoriums have absorbents on the wall at the back to stop undue reflections. Curtains, carpets, etc., also absorb sound to a certain extent. Clothes that people wear also make a difference. Generally, musicians prefer that some sound is reflected, but for speeches it is desirable that the sound fades out very quickly. Therefore, in good halls there is an arrangement to remove absorbent materials if music is being played. Nowadays sound absorbing materials are used at a number of places, such as offices, aeroplanes, hospitals and factories, to cut down noise so that people can work and stay in better conditions. Too much of sound leads to nervous strain.

15.6 Speed of Sound

When a starter in an athletic event fires a gun, the sound is heard a fraction of a second after the smoke is seen from the finish line of a 100 m track. Spectators watching a game of cricket hear the sound a split second after a batsman makes a stroke. Obviously, sound travels fast enough but not as fast as light does.

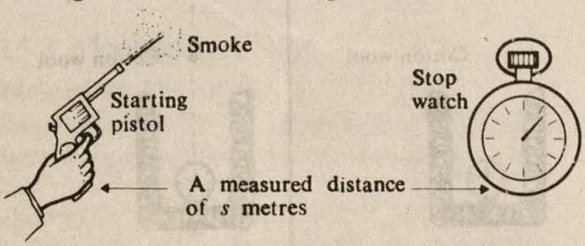


Fig. 15.8

A person fires a starter pistol and another person standing at a distance holding a stop watch measures the length of time between seeing the puff of smoke and hearing the bang of the starter pistol. If the distance from the pistol is measured, the velocity of sound can be found from the formula:

$$\text{Velocity of sound} = \frac{\text{distance}}{\text{time}} \text{ m/s}$$

or

$$v = \frac{s}{t} \text{ m/s}$$

As you know the velocity of light is very high (3×10^8 m/s). Consequently, the time taken by light to travel this distance is negligible. Therefore the time noted above can be taken to be the time taken by sound to travel this distance.

In order to eliminate the error due to the velocity of wind, repeat the experiment by firing the gun from the other side and take the mean of the two velocities. The temperature correction should be applied to the result for finding velocity of sound at 0°C according to the formula:

$$v_0 = v - 0.6t \text{ m/s}$$

as the velocity of sound increases by 0.6 m/s for 1°C rise of temperature. In the above formula, t is the atmospheric temperature in degrees celsius.

15.7 Distance of Lightning

The above idea can be used to find how far away the lightning is taking place. The time between the seeing of lightning and hearing of the thunder is measured. Knowing the speed of sound, the distance between you and the lightning can be worked out:

$$\text{Distance} = \text{velocity of sound} \times \text{time}$$

$$\begin{aligned} s &= v \times t \text{ m} \\ &= 333 \times t \text{ m} \\ &= \frac{333}{1000} t \text{ km} \\ &= \frac{t}{3} \text{ km} \end{aligned}$$

15.8 Echo

On making a loud sound while standing at a distance from a wall or a cliff, you may hear a repetition of it after reflection from the far off surface. This is called an echo.

An **echo** *is the repetition of a sound, caused by reflection of sound waves from a far off surface.*

In order to hear an echo separately, the reflected sound should come after 1/10th of a second. This is because the sensation of a note persists in our ears for 1/10th of a second. Hence, the reflected sound should come after covering a distance of $340 \times 1/10 = 34$ m. Hence, the far off surface should be at the least 17m away. Also the far surface should be large, otherwise the intensity of the reflected waves will be less and we may not hear it at all.

If a sound is made in between two reflecting surfaces not very far off from each other, the sound waves get reflected many times from one surface to the other. The reflected sounds are not heard separately but get merged with the original sound. The observer then hears a long drawn impression of his sound gradually dieing away. This is called **reverberation**. To avoid reverberations in halls sound absorbers are provided.

Bats use the phenomenon of echoes to avoid obstacles when flying in the dark. A bat while flying emits squeaks of very high frequency (ultrasonics) which are not audible to the human ear, but the bat's ears are able to respond to them. These high frequency waves get reflected from obstacles and the echoes allow the bat to sense the obstacles and avoid them. These high frequency waves are of short wave lengths, and are therefore reflected even from small obstacles. The principle is applied in the SONAR (sound navigation and ranging) systems used by trawlers and ships to detect rocks etc. in the sea, and to calculate their distance from the ship. SONAR also uses ultrasonic sound waves.

15.9 Velocity of Sound from Echo

The velocity of sound can also be measured by a method based on echo. A person with a starting pistol and a stop watch stands at a measured distance from a high wall. He fires the pistol and measures the time taken by the echo to return. This is the time taken by the sound to travel to the wall and back. The velocity of sound is then worked out as below:

$$\text{Velocity} = \frac{2 \times \text{distance from wall}}{\text{time}}$$

$$v = \frac{2d}{t}\,\text{m/s}$$

If the echo of a hand clap is loud enough to be heard, then a more accurate measurement can be made. Adjust your rate of clapping such that after hearing the echo of the first clap, a second clap is made immediately—this is repeated 10 times in quick succession. The time for 10 sound reflections is thus determined, 1/10 of which is the accurate time *t* for one forward and back movement.

15.10 Echo Sounding

Boats frequently carry an instrument called an *echo sounder* which measures the time between the sending out of a pulse and receiving an echo from the sea bed. Knowing the velocity of sound in water, which is about 1450 m/s, the depth of the sea-bed can be worked out from the formula given below:

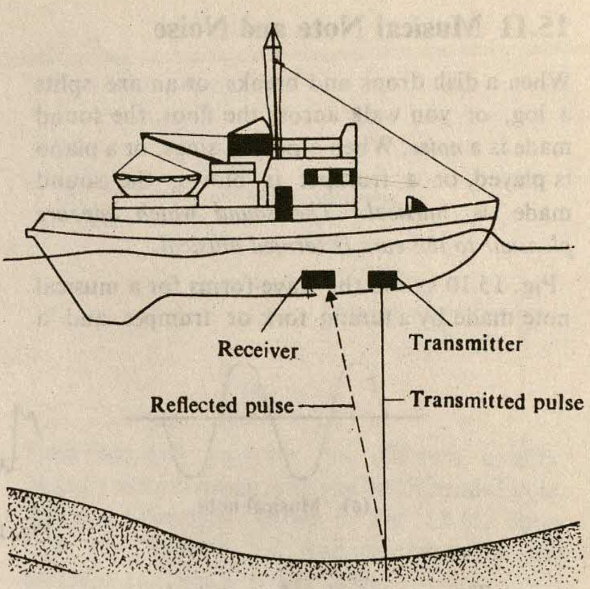


Fig. 15.9

$$\text{Depth} = \frac{\text{velocity of sound in water} \times \text{time}}{2}$$

$$d = \frac{v \times t}{2}\,\text{m}$$

EXAMPLE 1. (a) The sound of a gun was heard 8 km away, 24s after the flash was seen. Calculate the velocity of sound. (b) The man firing the gun heard an echo of the report from a cliff 15s after the gun was fired. How far from the gun was the cliff?

Solution

(a) $\text{Velocity} = \frac{\text{distance covered}}{\text{time taken}} = \frac{8\text{ km}}{24\text{ s}}$

$= \frac{8000\text{ m}}{24\text{ s}} = 333.3\text{ m/s}$

(b) Let the distance of the cliff be d m. Then in 15 seconds distance covered $= 2d$

$\therefore \quad t = \frac{2d}{v}$ or $d = \frac{tv}{2} = \frac{15 \times 333.3}{2} = \frac{4999.5}{2}$

$= 2499.75\text{ m} \simeq 2500\text{ m} = 2.5\text{ km}$

15.11 Musical Note and Noise

When a dish drops and breaks, or an axe splits a log, or you walk across the floor, the sound made is a *noise*. When a person sings, or a piano is played, or a trumpet is blown, the sound made is *musical. The sound which appears pleasant to the ears is termed musical.*

Fig. 15.10 shows the wave-forms for a musical note made by a tuning fork or trumpet and a noise. The wave-form of a musical note keeps repeating the pattern, although in some cases the pattern may be complicated. The wave of a noise is irregular with no pattern. A musical note has a definite wave length or frequency while a noise does not. There is, however, no clear cut rule to distinguish between a musical note and a noise.

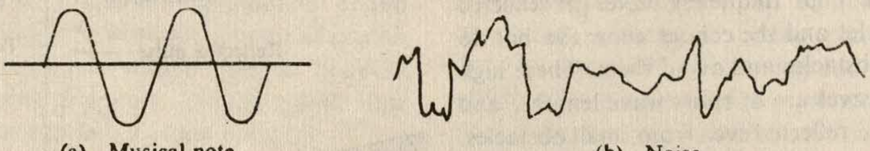

(a) Musical note (b) Noise

Fig. 15.10

15.12 Characteristics of a Musical Note

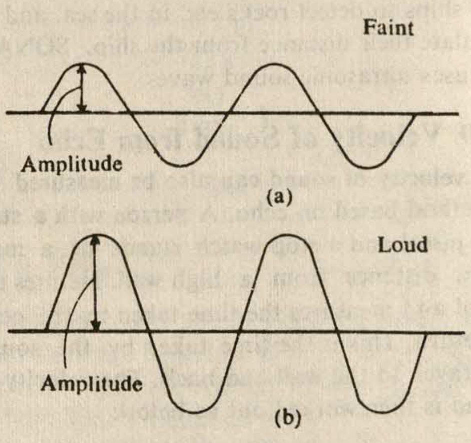
The roaring of a lion is loud while a whisper is soft; the chirping of sparrows is shrill while the brawl of a bull dog is flat. A note struck on a piano is more melodious than a similar note played on a harmonium. On the basis of physiological sensations produced by different notes, waves have certain fundamental properties as follows:

1. *Loudness*

If you tap a drum lightly, it transmits less energy to the air and the note produced is less loud. On tapping the drum hard, more energy is transmitted to the air and the note produced is louder or more intense. If on an oscilloscope screen (something like a picture tube in a T.V. set) we watch the graph of the sound produced, it is observed that whenever the sound gets louder, the amplitude of the graphed wave increases (Fig. 15.11). We may say that **loudness** *of a sound as we hear depends on the amplitude, or the power, of the sound wave.* Actually, loudness depends upon the square of the amplitude.

2. *Pitch*

Activity 6. Take a siren which consists of a metal disc with holes punched on it in circles. There are more holes in the outer circles than in the inner ones. The disc can be rotated about a horizontal axis *c* and through a jet, air can be blown through the holes (Fig. 15.12).



(a)

(b)

Fig. 15.11

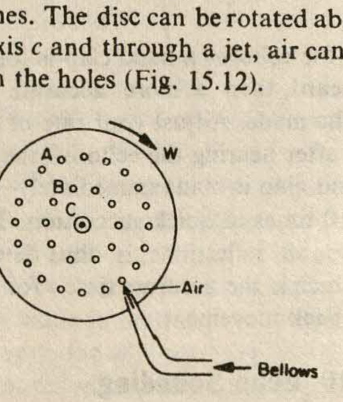


Fig. 15.12 Siren

Rotate the disc and blow air when the jet is facing against the outer circle of holes *A* and then against the inner circle *B*. In the first case the frequency of sound produced is greater and the sound heard is shriller than in the second case.

Pitch *is the shrillness or flatness of the sound heard and depends upon the frequency. More the frequency higher is the pitch.* Fig. 15.13 shows the wave-forms of two sounds of the same loudness but different pitch.

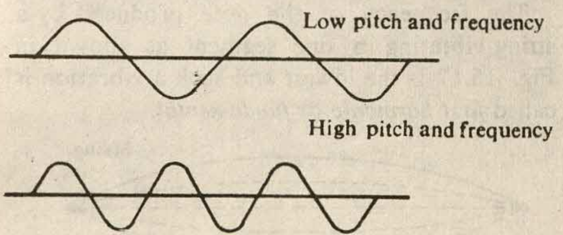


Fig. 15.13

Frequency is a major factor in determining the pitch of a sound, but the two are quite distinct. Frequency is the physical property of a sound wave and does not depend upon the presence of the listener. Pitch is a physiological or sensory characteristic; it is what you hear.

3. *Quality*

It is a common experience that even when two notes have the same amplitude (loudness) and the same frequency (pitch), they are not necessarily the same. For example, if you play the same note (say *sa*) on two stringed instruments, guitar and a sitar, you would easily be able to distinguish between the two notes. *The property by which one can distinguish between two notes of the same loudness and pitch is called* **quality.** *It depends upon the form of the wave which in turn depends upon the presence of overtones* (notes having frequencies which are simple multiples of the fundamental note).

The sound wave-forms shown in Figs. 15.11 and 15.13 are those of pure notes. A pure note sounds rather flat or dull. The quality of a note comes from the presence of faint overtones. Fig. 15.14 shows wave-forms having the same frequency and loudness but different quality being sounded along with the fundamental note. The wave-forms, as shown in Fig. 15.15, show how the fundamental and an overtone will combine to form a 'richer' note.

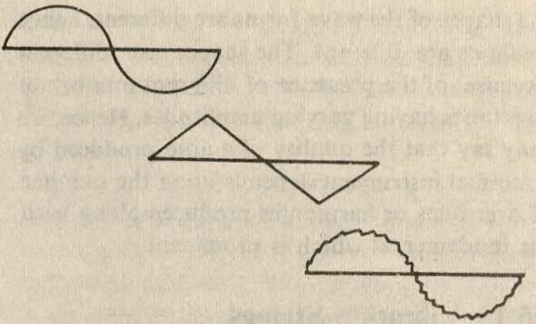


Fig. 15.14

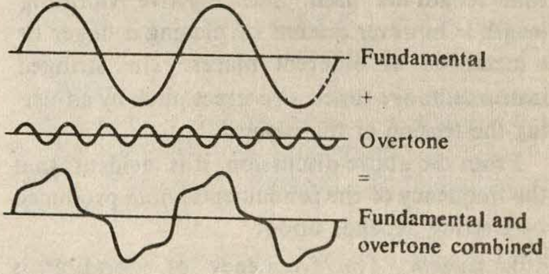


Fig. 15.15

Fig. 15.16 shows the wave-forms of the notes produced by a tuning fork, a violin, and a clarinet. All the wave-forms have the same wave length and therefore the same pitch, but

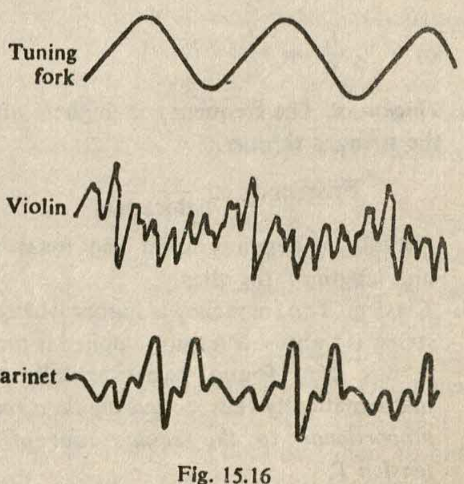


Fig. 15.16

the shapes of the wave-forms are different; hence qualities are different. The shapes are different because of the presence of different number of overtones having varying amplitudes. Hence, we may say that the quality of a note produced by a musical instrument depends upon the number of overtones or harmonics produced along with the fundamental which is prominent.

15.13 Vibrating Strings

In most of the musical instruments, notes are produced by vibrating strings of different lengths, varying thicknesses and tensions. In a harp and a piano, a number of strings of different length and thickness are used while in a guitar and sitar four strings of different thickness but same length are used. The effective vibrating length is however altered by placing a finger or a metal rod at different places. The stringed instruments are tuned to correct pitch by adjusting the tension of the strings.

From the above discussion, it is evident that the frequency of the fundamental note produced by a string depends upon:

1. *Length*: The frequency of vibration is higher when the string is shorter. In other words,

$$\text{Frequency} \propto \frac{1}{\text{vibrating length}}$$

or $$f \propto \frac{1}{l}$$

or $$\frac{f_1}{f_2} = \frac{l_2}{l_1}$$

2. *Thickness*: The frequency is higher when the string is thinner.

$$\text{Frequency} \propto \frac{1}{\text{thickness}}$$

Actually, it depends upon the mass per unit length of the string.

3. *Tension*: The frequency is higher when the string is tighter or tension applied is more. It has been found experimentally and mathematically that *frequency is directly proportional to the square root of the tension T.*

$$\text{Frequency} \propto \sqrt{\text{tension}}$$

or $$f \propto \sqrt{T}$$

15.14 Harmonics or Overtones

The vibrating string is held fixed at both ends—at these points the string does not vibrate at all. The 'no vibration' points are called *nodes*. The string vibrates most at the centre. 'A maximum vibrational' point is called an *antinode*.

The frequency of the note produced by a string vibrating in one segment as shown in Fig. 15.17 is the lowest and such a vibration is called *first harmonic* or *fundamental*.

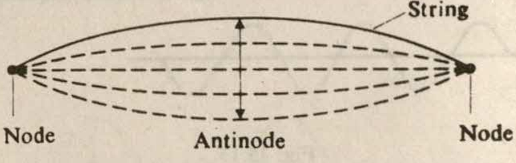


Fig. 15.17

If the string is slightly pressed in the centre, then a node is made there. By plucking in the middle of any one section, the string begins to vibrate in two segments as shown in Fig. 15.18a with a frequency double of the fundamental. Such a vibration is called *second harmonic* or *first overtone*.

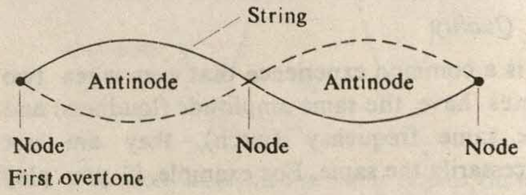


Fig. 15.18 (a)

The third harmonic or second overtone is produced when the string is lightly pressed at two places, one-third and two-thirds of the way along and then any one section is plucked (Fig. 15.18b).

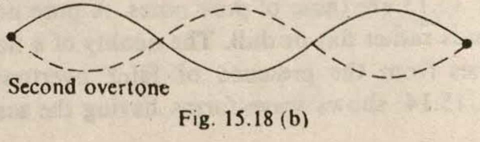


Fig. 15.18 (b)

15.15 Forced and Natural Vibrations

Whenever an object vibrates freely it does so with its natural frequency. Quite often vibrations may be induced in a body because of another vibrating object, kept close to it or in contact with it. The body is then said to have **forced** or **sympathetic vibrations.** For example if we press the stem of a vibrating tuning fork over a table top, a loud sound is heard. This is because the table top is forced to vibrate. Since its surface area is large a loud sound is produced. Similarly when a vibrating tuning fork is pressed on a sonometer or is held over the mouth of an air column, then the sonometer wire or the air enclosed in the air column begin to vibrate with forced or sympathetic vibrations.

15.16 Resonance

It is often observed that when a particular note is struck on a piano or harmonium, some freely hanging articles (say ornaments) close to the instrument begin to jingle. It is a common experience that in order to swing a garden swing to a great height the pushes should be applied at proper intervals. Why? Let us perform an experiment to understand this.

Activity 7. We know that the time period or the frequency of a pendulum depends upon its length; the greater its length the smaller is its frequency. From a light iron bar held straight between two clamp stands, suspend four pendulums as shown in Fig. 15.19. The pendulums *A* and *B* are of equal length, *D* is shorter and *C* longer.

Oscillate the pendulum *A*. You will find that *B* soon starts vibrating with the same frequency. This is because *A* produces vibrations which arrive at *B* fitting in with its own natural frequency of vibration. The motion of *B* is therefore built up and it vibrates with a large amplitude.

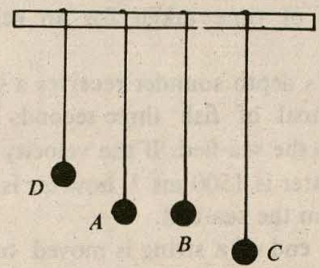


Fig. 15.19

The pendulums *C* and *D* first make irregular motions and eventually settle down to vibrate with the frequency of *A* but with smaller amplitudes than that of *B*. The vibration produced by *A* does not match the natural frequency of vibration of *C* and *D* as the lengths of *C* and *D* are different. *B* is said to be vibrating in **resonance** with *A* while *C* and *D* are said to have **forced vibrations.**

When a body vibrates, it induces vibrations in neighbouring bodies also. If a neighbouring body has the same natural frequency as that of the vibrating body, then it vibrates with maximum amplitude and the phenomenon is called **resonance.**

Whenever a particular note is struck on a piano, a hanging ornament begins to jingle if its natural frequency is equal to the frequency of the note produced.

Sometimes the body of a bus begins to rattle when it is driven at a particular speed. This happens when the frequency of vibration of the piston becomes equal to the natural frequency of vibration of the bus body. The body then vibrates in resonance with a large amplitude.

In a radio receiver when the capacity of the variable capicitor is so altered that the frequency of the tuned circuit becomes equal to the frequency of the incoming radio signal, resonance is achieved. The small alternating e.m.f. set up in the aerial system builds up a similar e.m.f. of large amplitude in the tuned circuit.

In order to achieve resonance in a stretched string, a paper rider is placed in the middle of the string and the stem of a vibrating tuning fork is pressed on the sonometer board. The vibrating length or the tension of the string is then altered to change its natural frequency of vibration. When resonance occurs the paper rider flies off. This happens because, when resonance occurs between the string and the tuning fork, the string vibrates with a large amplitude and the rider is thrown off.

When you walk on a long plank or lightly constructed bridge, the impulses produced by your step cause the plank or bridge to vibrate. If vibrations caused by the steps have the same frequency as the natural frequency of the bridge, then the latter is likely to vibrate violently and you may be thrown off. That is why soldiers marching across a bridge are ordered to march out of step.

QUESTIONS

1. How is sound produced? Why can sound not travel through vacuum?

2. How can you show that a medium is necessary for the propagation of sound?

3. Describe some evidence to show that sound is transmitted as a wave. Are sound waves transverse or longitudinal?

4. Explain the process by which the sound of your voice or a tuning fork is transmitted through the air and is heard by another person.

5. What is a longitudinal wave? In which ways are the sound waves different from light or electromagnetic waves?

6. Describe a method to find the velocity of sound in air. What precautions would you observe in conducting the experiment. In which of the three states of matter is the speed of sound the maximum and in which is it minimum?

7. A person sees the smoke from a starting pistol 0.9 seconds before he hears the bang. If the pistol is 280 m away, what is the speed of sound in air?

8. The speed of sound in air is 340 m/s. If you hear the thunder 5 seconds after you see the lightning, how far away has the lightning occured?

9. What is an echo? What are the conditions necessary for the production of an echo?

10. Give a method to find the velocity of sound in air based upon the phenomenon of echo.

11. Explain how an echo-sounder works. The echo-sounder on a boat sends down a pulse and receives its echo 0.3 seconds later. If the velocity of sound in water is 1445 m/s, how deep is the water?

12. What is the effect, if any, on the speed of sound in air if:

(a) frequency of the sounding object is increased;

(b) the loudness of the sound decreases;

(c) the temperature of air is raised.

13. Draw the wave-forms which are produced by two notes of (a) the same pitch but different loudness, (b) the same loudness but different pitch and (c) different quality.

14. Define the three characteristics of a musical note. Illustrate your answer with suitable diagrams.

15. A man is standing between two cliffs. The one in front is at a distance of 85 m while the one at the back is 170 m away from him. He blows a whistle loudly and hears two echos, one after the other.

Explain how this can happen and explain how long the first echo took to reach the man after he blew the whistle. (The velocity of sound in air is 340 m/s.)

16. What is an echo? What two factors affect the length of time taken for an echo to be heard?

A ship's depth sounder receives a weak echo from a shoal of fish three seconds before the echo from the sea-bed. If the velocity of sound in sea water is 1500 ms^{-1}, how far is the shoal of fish from the sea-bed.

17. One end of a string is moved to and fro so that a wave as shown in Fig. 15.19 is produced.

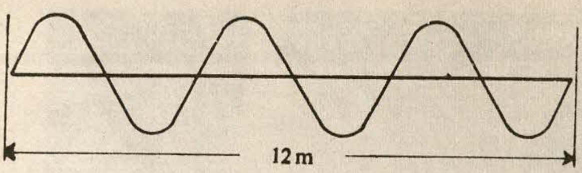


Fig. 15.19

(a) What is the wave length?

(b) If it moved to and fro 2 times a second, what is the frequency of the wave?

(c) What is the velocity of the wave?

18. Fig. 15.20a shows the trace on a cathode ray oscilloscope screen obtained when three notes are sounded in succession in front of a microphone connected to the oscilloscope.

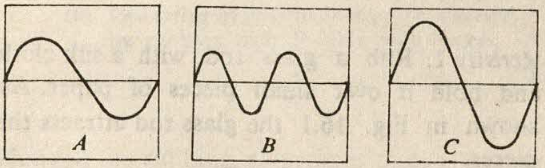


Fig. 15.20 (a)

(i) In what way (or ways) does note *B* differ from note *A*?

(ii) In what way (or ways) does note *C* differ from *A*?

19. Fig. 15.20b shows a stretched string vibrating at its fundamental frequency.

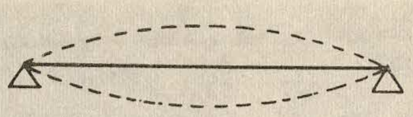


Fig. 15.20 (b)

(i) Copy this diagram and draw two others to show the wire vibrating at its next two high frequencies. Mark on your diagrams the positions of nodes and antinodes.

(ii) State two factors which affect the frequency of a fundamental note produced by the string.

(iii) Why does the quality (or timber) of the sound produced by a violin differ from that produced by a piano?

20. State two ways in which a stretched wire can be adjusted to resonate with a fork.

How is the frequency of a note emitted by a stringed instrument altered by a player (i) during tuning, and (ii) while playing a melody? How does the player increase the intensity of the sound?

21. What do you mean by resonance? Explain your answer by stating three examples.

22. A man fires a shot and hears its echo from a cliff after 2 seconds. He walks 85 m towards the cliff and fires the gun again and hears the echo of the second shot now after 1.5 seconds. Calculate the velocity of sound. How far was the man from the cliff when he fired the first shot?

16

Electrostatics and Atomic Structure

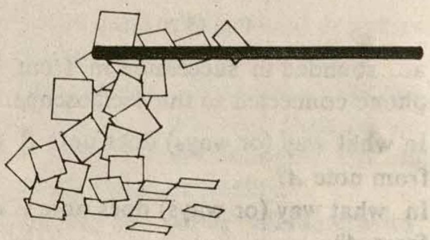
Six centuries before the Christian era, a Greek scholar named Thales pointed out that *amber* which is like natural plastic, when rubbed has the ability to attract small, light objects. The Greek word for amber is *elektron*, from which have come our modern terms *electricity* and *electron*.

Other electrical phenomena, such as lightning and beautiful northern lights which are seen at dusk in northern parts of Canada, etc. were known to man thousands of years ago. However, man has begun to understand that all these are related to the electrical nature of matter from only 200 years ago. Since then we have come a long way and know a great deal more about the nature and behaviour of atoms and electrons.

16.1 Electrification by Friction

When you comb your hair with a plastic comb, your hair clings to the comb. In fact sparks can often be seen and crackling sound can be heard, if you comb your dry uncoiled hair sitting in front of a mirror in the dark. Similarly an inflated rubber balloon on rubbing with a wall often sticks to it. We say that on rubbing, these objects acquire electrical charges. Their charges stay on them in dry weather. In humid weather the charges tend to leak off the rubbed objects to the atmosphere through the humid air. Charges so obtained on rubbing are called *frictional* or *static* (stationary) charges.

Activity 1. Rub a glass rod with a silk cloth and hold it over small pieces of paper. As shown in Fig. 16.1 the glass rod attracts the pieces.



A glass rod charged by rubbing at one end will attract paper only at that end.

Fig. 16.1

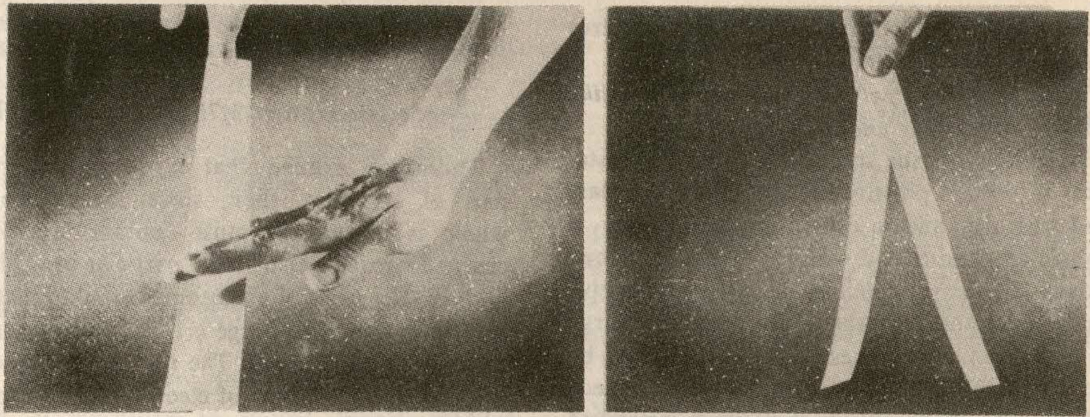
Similarly an ebonite rod on rubbing with fur or wool; a polythene strip on rubbing with cloth and a plastic strip on rubbing with cotton acquire this property of attracting other objects and are said to be charged or electrified.

The *electrostatic force*, the force between static charges, may also be repulsive in nature.

Activity 2. Rub two thin vinyl plastic or polythene strips with your fingers as shown in Fig. 16.2a. After a few quick strokes you would observe that they repel each other and stand out from each other as shown in Fig. 16.2b.

16.2 Two Kinds of Charges

So far you have learnt that when objects are



(a) Two strips of polythene can be charged by rubbing them briskly with fingers.

(b) As a result of being charged, the two strips repel each other.

Fig. 16.2

charged by rubbing, sometimes there is attraction and sometimes repulsion. Let us do some simple experiments to know more about the nature of charges.

Activity 3. Rub an ebonite rod with fur and suspend it in a wire stirrup by a *nylon* thread from a stand. Bring another similarly charged ebonite rod near it. The suspended rod is repelled.

Now take a glass rod and charge it by rubbing with silk and bring it near the charged suspended ebonite rod. This time the ebonite rod is attracted.

This experiment clearly shows that charges on the ebonite and the glass rods are not of the same type. Benjamin Franklin gave specific names to these charges. The charge on the glass rod was named *positive* and the one on the ebonite rod was termed *negative*.

Now remove the ebonite rod and suspend the charged glass rod in its place. On bringing another charged glass rod, repulsion is observed.

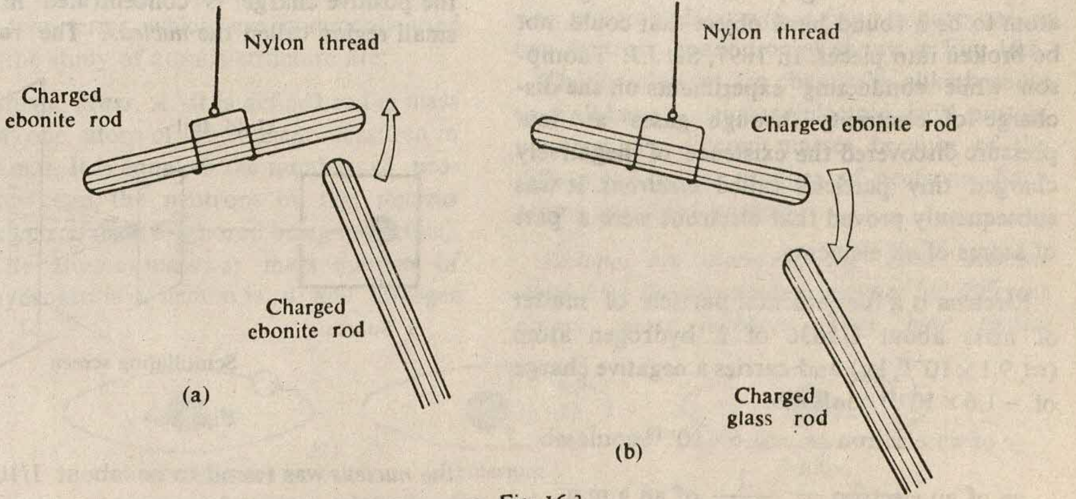


Fig. 16.3

This gives us an important **rule about electrostatic forces** which states that:

Like charges repel one another and unlike charges attract one another.

Traditionally, the standard way in electrostatics to obtain positive charge is to rub a glass rod with silk, and to obtain negative charge is to rub an ebonite rod with fur or flannel. Nowadays, the use of *cellulose acetate* for positive and polythene (alkathene) for negative charge is preferred, since these are less affected by damp conditions. Also a cotton cloth piece may be used to rub both of them instead of fur or silk.

16.3 Atomic Structure

To understand about the effects of static electricity it is necessary to know about the structure of matter. All matter is made up of tiny particles called *atoms* which may or may not exist freely. There are over 100 different kinds of atoms and they combine with one another in different ways to form groups of atoms called *molecules.*

Atom is too small to be seen with even the best known optical microscope. One cubic centimetre of air at normal pressure contains about 54,000,000,000,000,000,000 ($= 5.4 \times 10^{19}$) atoms. This is almost 20 billion times the population of the entire world.

Over 150 years ago, scientists thought an atom to be a round hard object that could not be broken into pieces. In 1897, Sir J.J. Thompson while conducting experiments on the discharge of electricity through gases at low pressure discovered the existence of negatively charged tiny particles called *electrons.* It was subsequently proved that electrons were a part of atoms of all elements.

Electron is a fundamental particle of matter of mass about 1/1836 of a hydrogen atom ($\simeq 9.1 \times 10^{-31}$ kg) and carries a negative charge of -1.6×10^{-19} coulomb.

$$e \text{ of an electron} = -1.6 \times 10^{-19} \text{ coulomb}$$

$$m \text{ of an electron} = \frac{1}{1836} \text{ of an a.m.u. (atomic-mass-unit)}$$

$$\simeq 9.1 \times 10^{-31} \text{ kg}$$

$$\frac{e}{m} \text{ of an electron} = 1.76 \times 10^{11} \text{ coulomb/kg}$$

Thompson argued that if electrons were a part of an atom, then, since the atom as a whole is neutral, it must contain positively charged particles also. Such particles are called *protons.* The mass of a proton is equal to that of an H-atom and its charge is equal and opposite to that of an electron. The number of protons is equal to the number of electrons in an atom, so that the atom as a whole is neutral.

Proton is a fundamental particle of an atom carrying 1 unit positive charge ($= +1.6 \times 10^{-19}$ C) and has a mass of 1 a.m.u. The ratio *e/m* of a proton is 9.58×10^{7} C/kg.

How are electrons and protons arranged in an atom? Some scientists suggested that protons are embedded in the entire mass of an atom in the same way as raisins are present in a pudding. To investigate the interior of an atom, scientists at Manchester in England performed the well known experiment in which they bombarded a thin leaf of gold with positively charged alpha particles (about which you will study later on). While most of the alpha particles remained undeflected, a few were deflected through large angles. This suggested that, while most of the space in an atom is hollow, the positive charge is concentrated in a very small region called the *nucleus.* The radius of the *nucleus* was found to be about 1/100,000th part of the radius of an atom.

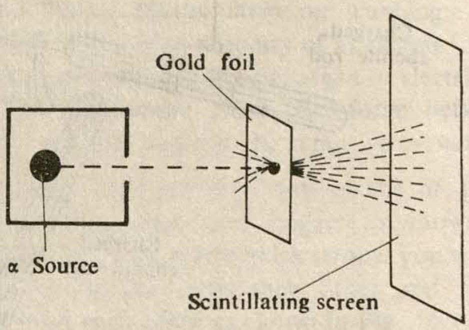


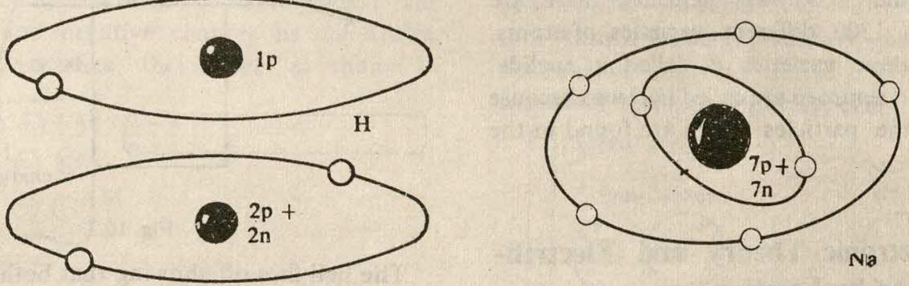
Fig. 16.4

In 1932, J. Chadwick discovered the *neutron.* **Neutron** *is a fundamental particle of an atom of mass equal to 1 a.m.u. but carries no charge.*

Two years later, Neils Bohr, a student of Rutherford showed that electrons probably revolve about the nucleus in certain orbits called energy levels.

It may interest you that Sir J.J. Thompson, J. Chadwick and Neils Bohr were all awarded the Nobel Prize for their work on the structure of the atom.

We now believe that an atom has a central nucleus consisting of tightly packed protons and neutrons, with electrons moving around it at various energy levels (orbits). The atoms are all built on this pattern and differ from one another by the number of protons and neutrons contained in the nucleus. Fig. 16.5 gives models of atoms of hydrogen, helium and nitrogen.



(a) (b)

Fig. 16.5

The two terms which are commonly used during the study of atomic structure are:

1. *Atomic Mass, A*: It is defined as the mass of one atom of the element measured in a.m.u. It is equal to the number of protons and the neutrons in the nucleus (electron mass is ignored being negligible). The atomic mass or mass number of hydrogen is 1, helium is 4 and nitrogen is 14.
2. *Atomic Number, Z*. It is defined as the number of unit positive charges or protons in the nucleus of the atom. The number of electrons revolving round the nucleus is also Z and this governs the chemical properties of the element.

If the chemical symbol of an element is X, it is usually written as $^{A}X_{Z}$ to indicate its atomic mass and atomic number. For example, nitrogen atom is usually written as $^{14}N_{7}$ and sodium as $^{23}Na_{11}$.

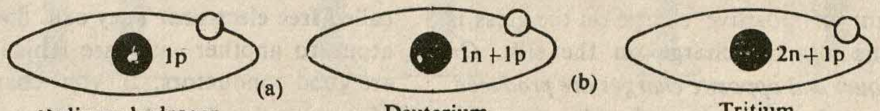
Some elements have fractional atomic masses because of the presence of isotopes in specific ratios.

16.4 Isotopes

Almost all hydrogen atoms have one proton and one electron. However, a few will have one or two neutrons in addition as shown in Fig. 16.6.

The three atoms are chemically alike because they all have 1 planetary electron and 1 proton, but they have different masses because of the difference in the number of neutrons. Such atoms are called **isotopes**.

Isotopes are atoms of the same element which have the same atomic number but different atomic mass numbers. They have similar



(a) Ordinary hydrogen (b) Deuterium (c) Tritium

Fig. 16.6

chemical properties but different physical properties. 99.985% of all naturally occuring hydrogen atoms are of the first type. Nearly all of the rest are deuterium or heavy hydrogen atoms.

Chlorine is a mixture of two isotopes, $^{35}Cl_{17}$ and $^{37}Cl_{17}$. The former is about 75.5% and the latter 24.5%. This is why the mean atomic mass of an atom of chlorine is 35.453. Each isotope of chlorine is composed of 17 protons, 17 electrons and either 18 or 20 neutrons. Almost every element has several isotopes, with the result that though there are only slightly more than 100 different known elements, there are more than 1300 different varieties of atoms. Each of these varieties is called a **nuclide**. Protons and neutrons are called **nucleons** because they are the particles which are found in the nucleus.

16.5 Electronic Theory and Electrification by Friction

According to the electronic theory, an atom is made up of electrons, protons and neutrons. Neutrons and protons are packed in the nucleus and are held together by strong nuclear forces. Around the nucleus revolve very light negatively charged electrons. Some of these are loosely bound and can be easily detached. An object acquires a charge when some electrons are lost or gained by it. Material that *gains* electrons becomes *negatively* charged and the one that *loses* electrons becomes *positively* charged.

When a glass rod is rubbed with silk, some of the electrons are detached from glass and get attached to the silk. Consequently, glass becomes positively charged and the silk negatively charged. The number of electrons lost by glass is equal to the number gained by the silk. Hence, the amount of positive charge on the glass is equal to the negative charge on the silk. *On rubbing, equal and opposite charges are produced.* We can, therefore, say that *electric charge is conserved.*

16.6 Conductors and Insulators

Activity 4. Coat a pith or a foam ball with powdered graphite paste to make it conducting and suspend it by a silken thread from a stand. Place a metal rod on a beaker and keep it near the ball in such a way that one end of the rod just touches the suspended ball. Touch the free end of the metal rod with a charged polythene strip as shown in Fig. 16.7.

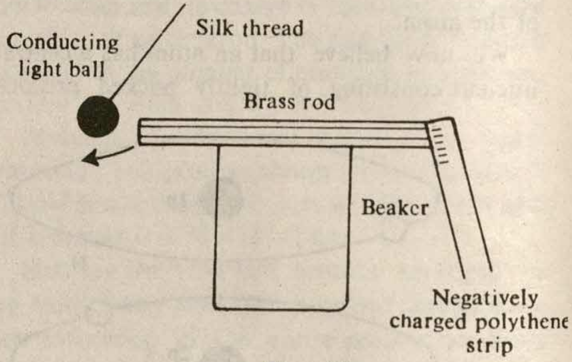


Fig. 16.7

The ball flies off showing that both the metal rod and the conducting ball have acquired a similar charge which has flowed from the strip through the rod to the ball.

Replace the metal rod with an ebonite or glass rod and repeat the experiment. The ball stays where it was. The experiment shows that a metal rod conducts electrical charge while an ebonite or a glass rod does not.

Substances like metals and carbon which allow the charge to pass through them are called good conductors and substances like glass, ebonite, polythene, plastic and rubber, etc. which do not conduct charges are called insulators.

The human body is a good conductor. If we touch a wire with electricity flowing through it, some of it passes through our body to the ground and we experience an 'electric shock'

In metals each atom has one or more electrons that are very loosely held. These are called **free electrons**. They can flow from one atom to another with ease. This is why metals are good conductors. If you charge one end of a metal rod with extra electrons, they will repel the free electrons which move further ahead, and soon the whole of the rod becomes charged.

In insulators, electrons are tightly bound to atoms and move either with great difficulty or do not move at all. This is why a charge given to one end of a glass, ebonite, plastic, wood or procelain rod, stays there and does not flow.

16.7 Electrostatic Induction

You have observed that a charged rod picks up bits of paper. Why? Let us understand this.

As a positively charged rod approaches the paper, it attracts the negatively charged electrons in each atom of the paper towards it. The positive and negative charges in the atoms, therefore, arrange themselves as shown in Fig. 16.8. The overall effect of this arrangement is that the surface layer of paper near the positively charged rod contains negative sides of atoms while the far off side contains the positive sides of atoms. Since the negative surface of the paper is nearer the positive charged rod, hence, the force of attraction is greater than the force of repulsion, and the piece of paper is attracted towards the rod. The surface of paper has been charged by *induction*. We may conclude that *induction preceeds attraction.*

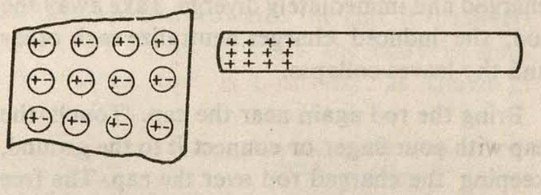


Fig. 16.8

When a charged body is brought near another object, the nearer end of the object acquires opposite charge and the farther end a similar charge. The two induced charges are equal and opposite. This phenomenon is called electrostatic induction.

16.8 Charging by Induction

Activity 5. Place two metallic spheres mounted on insulating stands side by side, so that they touch each other. Bring a negatively charged ebonite rod near the sphere *A*, but not touching it (Fig. 16.9a). The negative charge on the ebonite rod will repel electrons from sphere *A* to *B*; thus *A* becomes positively charged being deficient of electrons and *B* gets surplus electrons and becomes negatively charged.

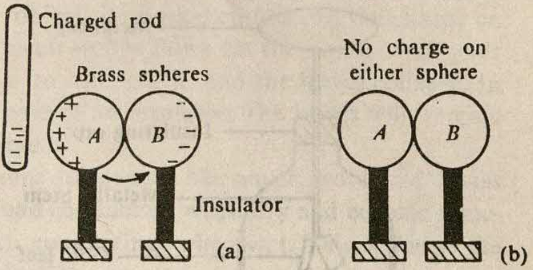


Fig. 16.9

If we remove the ebonite charge, surplus electrons from *B* flow back to *A* and the two spheres are left uncharged, see Fig. 16.9b. This shows that the two induced charges are equal and opposite.

Now again bring the charged ebonite rod near the two conducting spheres in contact with

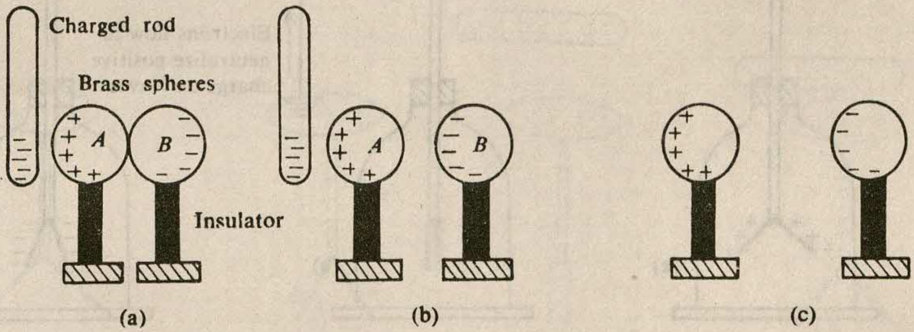


Fig. 16.10

each other (Fig. 16.10a). Separate the two spheres and then remove the ebonite rod. The sphere *A* is found to carry a positive charge and *B* a negative charge (Fig. 16.10c).

This experiment tells us how we can charge conducting objects by induction and also proves that the two induced charges are equal and opposite.

16.9 Gold Leaf Electroscope

The gold leaf electroscope is the oldest electrical instrument which was developed in 1787. It is used to detect and measure the quantity of charge. It mainly consists of a metallic cap and stem, fitted in a bell-jar through an insulating cork. At the bottom of the stem are mounted two gold leaves (Fig. 16.11).

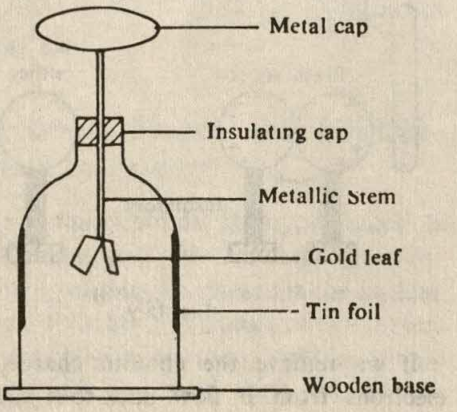


Fig. 16.11

When the cap is touched by, say a negatively charged body, electrons get transferred to the cap and flow down the rod to the leaves. Electrons on the leaves repel one another and cause spreading or divergence of the leaves. The divergence of the leaves can be used as a measure of the charge on the body.

When the charged body is removed, the leaves remain diverged because of the charge transferred due to *conduction*. The electroscope can also be charged by *induction*.

Activity 6. Bring a charged glass rod near the cap of an electroscope, but do not touch it. Induction takes place, the cap gets charged negatively and the leaves become positively charged and immediately diverge. Take away the rod, the induced charges neutralize each other and the leaves collapse.

Bring the rod again near the cap. Touch the cap with your finger or connect it to the ground, keeping the charged rod over the cap. The free charge on the leaves escapes to earth. Actually electrons flow from the earth to neutralize the free positive charge on the leaves as shown in Fig. 16.12b.

Remove your finger and then remove the charged rod. The negative charge on the cap becomes free and spreads to the leaves (Fig. 16.12c). The leaves diverge and remain diverged as the electroscope has been charged permanently by

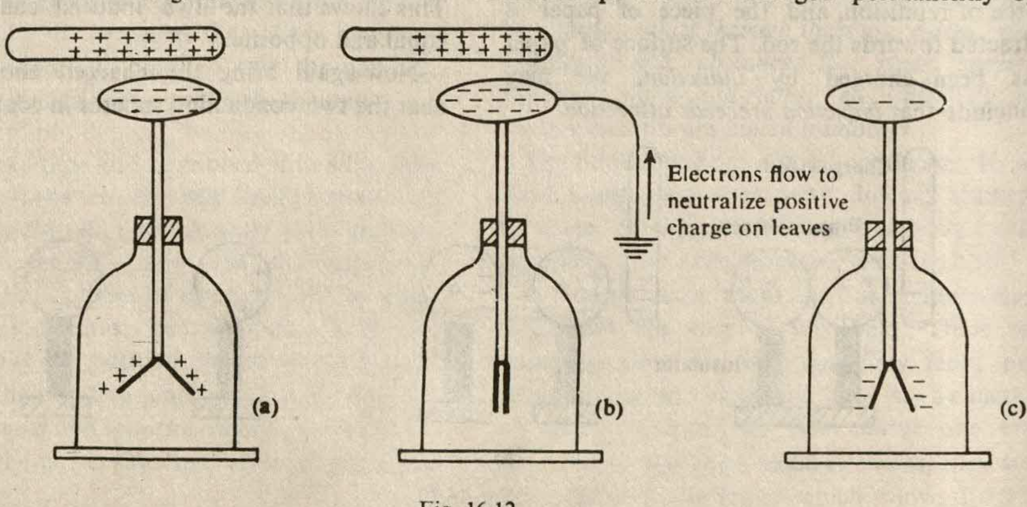


Fig. 16.12

induction (provided the charge does not leak off to the air).

In order to charge the electroscope positively by induction, a negatively charged body is used as an inducing charge.

Use of a Gold Leaf Electroscope

1. *To detect presence of charge*: Bring the body to be tested near the cap of an uncharged electroscope; if leaves diverge then the body is charged, otherwise not.

2. *To test the sign of charge:* Charge a gold leaf electroscope, say positively, as shown in Fig. 16.13(a) and note the divergence of the leaves, which is a measure of the charge present on them. Now bring a charged body from a height downwards towards the cap. If the divergence of the leaves increases, the body is similarly charged, that is positively, as shown in Fig. 16.13(b).

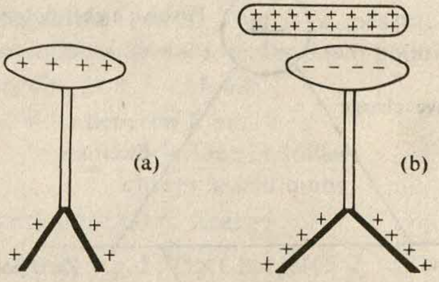


Fig. 16.13

If the divergence of the leaves decreases as shown in Fig. 16.14(b), the body is oppositely (i.e. negatively) charged.

If the body is strongly oppositely charged it is possible that while bringing it downwards the divergence may decrease at first, the leaves collapse as shown in Fig. 16.4(c) and then again diverge(Fig.16.4d). The leaves collapse when the entire positive charge on them is neutralized by the negative charge induced by the body. Subsequently the leaves become negatively charged by induction and diverge again.

While testing the body, it is necessary to bring the charged body *gradually downwards from a good height* and to carefully note the divergence.

3. *To test good and bad conductors*: Charge an electroscope, say positively. Touch the object under test with the cap of the electroscope. If the object is a good conductor, the charge on the electroscope flows via the object and your body to the earth and the leaves collapse. In the case of an insulator, the leaves will remain diverged.

Some substances like paper, wool and wood are bad conductors when dry and become somewhat conducting when wet. This is due to the conducting property of water.

16.10 Electrostatic Potential

On raising a body from the ground to a certain height, some work is done on the body against the force of gravity. This work is stored in the body as gravitational *potential* energy. On

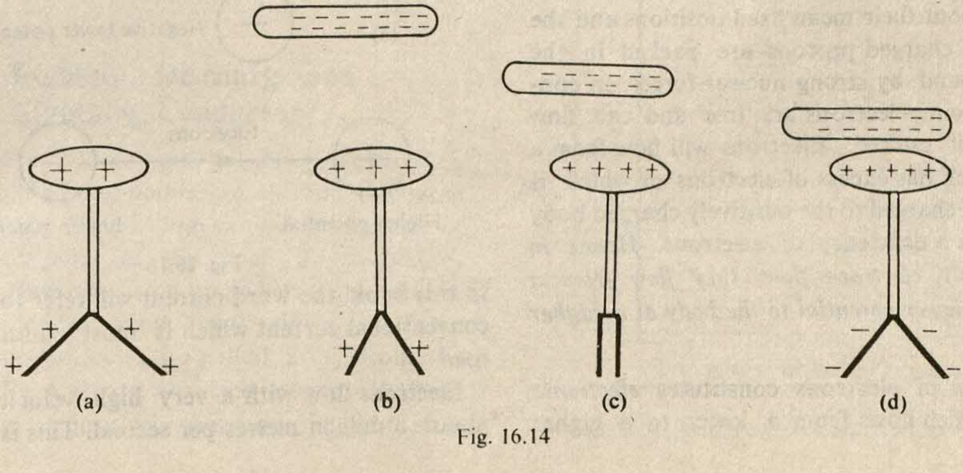


Fig. 16.14

releasing a body from a height, it always falls down to the Earth, i.e. from a higher potential energy position to a lower or zero potential energy position.

When a charged electroscope is touched with a finger or earthed, the leaves immediately collapse showing thereby that the charge has flowed either from the electroscope to the Earth via your body or vice versa.

Earlier scientists, knowing that water flows from higher to the lower level and heat flows from a higher to a lower temperature, assumed that the potential of the Earth is zero and the charge (positive) flows from higher potential to the lower potential till their potentials become equal (Fig. 16.15). Potential of a positively charged body is higher than zero and of a negatively charged body is lower than zero.

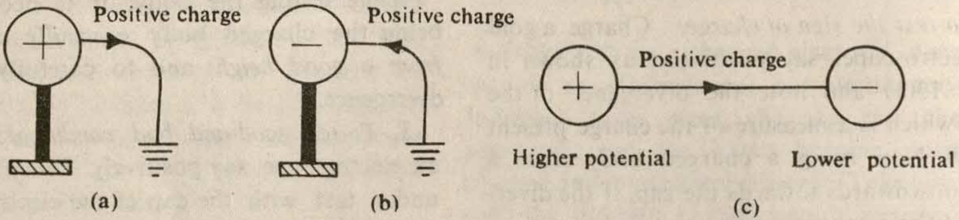


Fig. 16.15

We may conclude that **electrostatic potential** *is the physical state of a body which indicates the direction of flow of charge when the body is connected to the earth.*

We know that in solids only the atoms vibrate about their mean fixed positions and the positively charged protons are packed in the nuclei bound by strong nuclear forces. In conductors, some electrons are 'free' and can flow or shift if pushed. Electrons will flow from a body which has excess of electrons or which is negatively charged to the positively charged body which has a deficiency of electrons. Hence *in solids, only electrons flow; they flow from a body at a lower potential to the body at a higher potential.*

The flow of electrons constitutes *electronic current* which flows from a lower to a higher potential or from a negatively charged body to a positively charged body. Its direction is opposite to the *conventional current* which is considered to be the flow of positive charge.

Current is the flow of electric charge and is defined as the amount of charge flowing per second. It is measured in amperes.

$$\text{Current } I \text{ (amperes)} = \frac{\text{charge}}{\text{time}} = \frac{Q\text{(coulombs)}}{t\text{(seconds)}}$$

or
$$Q(\text{C}) = I(\text{A})\, t(\text{s})$$

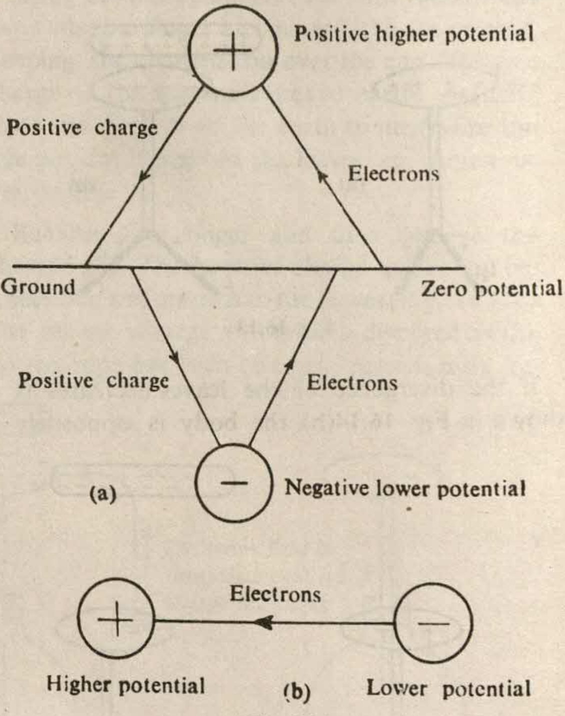


Fig. 16.16

In this book, the word current will refer to the conventional current which is most commonly used.

Electrons flow with a very high velocity of about a million metres per second. This is why when the supply is switched on at Bhakra dam it reaches Delhi which is hundreds of kilometres away from it within a very short time. In order to have a continuous flow of current, a constant potential difference is needed which we cannot have by electrostatic means.

16.11 Potential Difference

Imagine a large negatively charged object which is not free to move and a tiny positively charged object as shown in Fig. 16.17. They are very close to each other and attract each other by an electrostatic force.

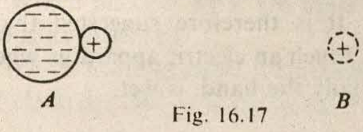


Fig. 16.17

Some mechanical work will have to be done in pulling the tiny charge against the force of attraction from *A* to *B*. This is a measure of the potential difference between two points, if the tiny charge is 1 coulomb.

P.D. in volts between *B* and *A*

$$= \frac{\text{work done in Joules}}{\text{charge in coulombs}}$$

or Work done (J) or Energy

$$= \text{p.d.(V)} \times \text{Charge(C)}$$

$$E = QV = VIt \qquad (\because Q = It)$$

The p.d. between any two points is 1 V when 1 J work is done in transferring 1 C charge from one point to the other.

16.12 Lightning Discharge and Lightning Conductor

If there is a large potential difference between two neighbouring points, an electric discharge in the shape of 'sparking' can occur. Because of the large potential difference, a tremendous electric 'pressure' is set up and insulation of the air between the points 'breaks down'. Electrons of the air molecules are pulled away from the molecules and are attracted towards the high potential or positively charged point. The positive ions so formed are attracted towards the negatively charged point. Electrical energy thus released is transformed into heat, light and sound energy and 'sparking' is observed.

In mid eighteenth century the American scientist Franklin Benjamin showed that during a thunderstorm, the clouds get charged. He concluded that lightning is a gigantic electric discharge which occurs because of the large potential difference between two clouds or between a cloud and the earth. The quantity of electricity which is discharged during lightning is usually not very large, but the potential difference driving it is so great that a tremendous amount of energy is liberated by it which can damage buildings and trees.

In order to protect tall buildings from being damaged by lightning, lightning conductors are provided. A lightning conductor consists of a

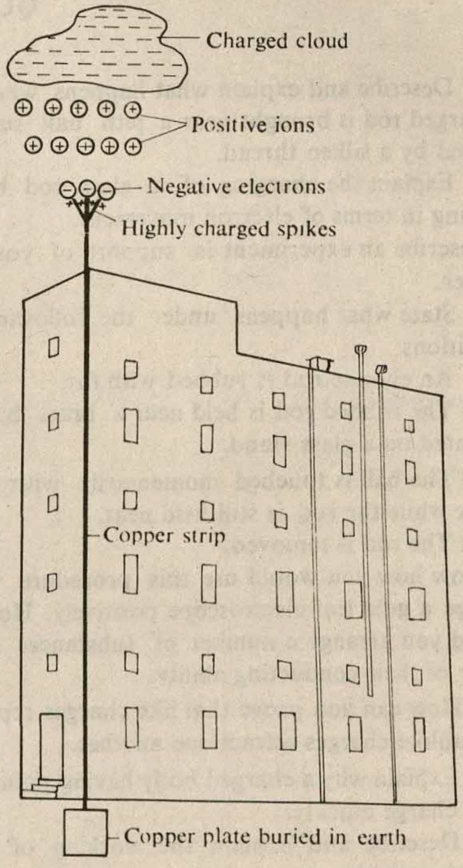


Fig. 16.18 Action of lightning conductor

thick copper strip which is fixed to an outside wall and has sharp spikes at the upper end and a copper plate at the lower end. The spikes project above the highest part of the building and the copper plate is buried deep into the earth (Fig. 16.18).

If a negatively charged cloud happens to pass over a building, a positive charge is induced on the building and the surrounding earth. Positive charge from the points of the conductor will tend to neutralize the negative charge on the cloud. Thus the chances of a lightning flash are diminished. Even if a flash occurs the conductor provides a better conducting path for the charge to escape to the earth and any damage to the building is prevented.

The human body is seriously damaged by rapid discharge through it of large amounts of charge at moderate potential. This discharge affects the nerves which control the body. Usually the intensity of discharge is not enough to seriously damage the body, as the body is not a good conductor of electricity. However, if the body is wet, much more serious shock is experienced because impure water is a good conductor. It is therefore suggested that one should not touch an electric apparatus when the body, specially the hand, is wet.

QUESTIONS

1. Describe and explain what happens when a charged rod is brought near a pith ball suspended by a silken thread.

2. Explain the charging of a glass rod by rubbing in terms of electron movement.

Describe an experiment in support of your answer.

3. State what happens under the following conditions:

(a) An ebonite rod is rubbed with fur.

(b) The rubbed rod is held near a brass ball mounted on a glass stand.

(c) The ball is touched momentarily with a finger while the rod is still held near.

(d) The rod is removed.

Show how you would use this procedure to charge a gold leaf electroscope positively. How would you arrange a number of substances in order of their conducting ability.

4. How can you prove that like charges repel and unlike charges attract one another.

5. Explain why a charged body having points loses charge quickly.

6. Describe and explain the working of a lightning conductor.

7. Explain the term *electrostatic induction*.

Given two metal spheres supported on insulating stands, describe how these can be charged with equal and opposite amount of charges.

8. What do you mean by good conductors and insulators? Why are metals good conductors? Explain this on the basis of the electronic theory.

9. Describe a gold leaf electroscope and illustrate your answer by drawing a labelled diagram. Show how it can be used to determine the sign of an electric charge.

If you are provided only with a negatively charged rod, how would you charge the electroscope: (a) negatively, and (b) positively.

Describe an experiment to show that, when charges are produced by friction, equal quantities of electricity of opposite signs are obtained.

10. Briefly describe the structure of an atom. Explain the meanings of the terms electrons, protons, neutrons and nucleus.

11. What do you mean by an isotope. Give the atomic structure of the two isotopes of chlorine.

12. The symbol for oxygen is O, for nitrogen N, for carbon C. With reference to the following nuclides, answer the questions that follow:

$$^{16}O_8;\ ^{16}N_7;\ ^{15}C_6;\ ^{15}O_8;\ ^{17}O_8;\ ^{15}N_7$$

(i) Which three nuclides are isotopes of each other?

(ii) Which nuclides have the most neutrons, and how many do they have?

(iii) Which nuclides have the same number of protons as neutrons?

(iv) Which nuclides have the same number of electrons as protons?

(v) Which nuclides have the maximum number of electrons and how many do they have?

(vi) Which nuclides have the largest mass number, and what is the number?

(vii) Which nuclides have the smallest atomic number and what is the number?

13. What determines the chemical behaviour of an element?

14. What do you mean by electrostatic potential?

Define the term potential difference and give the relation between charge, p.d. and energy.

15. Name and explain the unit in which potential difference is measured. Define coulomb.

17

Electric Cells

We have become so highly dependent on the use of electricity in our daily life that we often take it for granted. It lights, heats and cools our homes, provides us with entertainment and performs a number of daily routine jobs for us. T.V. sets, radios, cinema projectors, radar systems and computors cannot operate without electricity. It makes hair-driers, vacuum cleaners, refrigerators and electric irons work for us. Electricity is needed to make telephone and telegraph systems work. The uses of electricity are so numerous and so varied that it is difficult to list them all over here. It would make an immense difference to our lives if we had to live without it and then only would we realise how important electricity is to us.

In 1786, an Italian scientist called Galvani hung up a dissected frog from a brass hook which was touching the nerves of the frog's leg (Fig. 17.1). When one of the legs accidently touched an iron railing, Galvani noticed that the muscles of the leg moved and the dead frog gave a 'kick'. He thought that electricity was produced by the frog's legs and he called it 'animal electricity'.

His friend Volta, another Italian scientist, thought otherwise and believed that the movement of the frog's leg was caused by some action of the two metals and the solution in the nerve of the leg. Volta obtained a continuous current from the first simple cell, using zinc and copper plates in a salt solution.

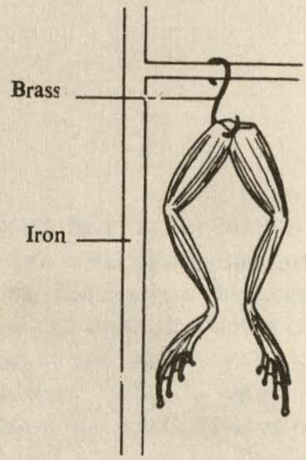


Fig. 17.1

17.1 Simple Voltaic Cell

This is the basic cell from which all others have been developed. In its simplest form, it consists of a copper plate and a zinc plate dipped into dilute sulphuric acid contained in a glass vessel as shown in Fig. 17.2.

The two plates are connected by wires to a torch-light lamp holder. When a torch bulb is screwed in, current flows and the lamp is seen to glow. The zinc dissolves making the zinc plate electron rich, and hydrogen is given off at the copper plate making it electron short. Electrons flow from zinc to copper in the outer circuit through the bulb causing it to glow. Hence, a simple cell converts chemical energy into elect-

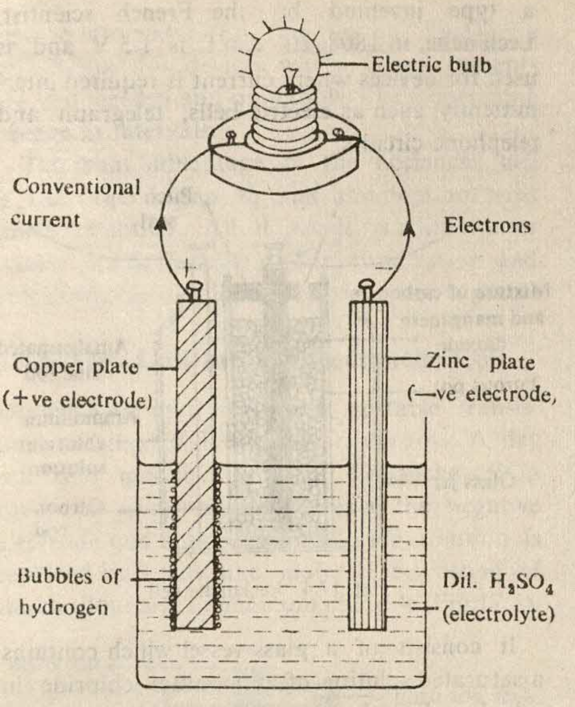


Fig. 17.2

rical energy. It is observed that the glow gradually becomes dimmer and dimmer and in a few minutes it goes out. If the copper plate is now removed, wiped with a piece of cloth to remove hydrogen which has collected there and then replaced, the bulb glows brightly again and in a minute or two again fades out.

The copper and zinc plates are called *electrodes* or the 'poles' of the cell and dilute sulphuric acid is the *electrolyte*. Zinc being electron rich serves as a 'negative pole' and copper acts as a 'positive pole'. In the outer circuit electronic current flows from zinc to copper and current (conventional) from positive copper to negative zinc.

17.2 Defects of Simple Voltaic Cell

The simple voltaic cell suffers from two defects known as (i) local action and (ii) polarization.

Local Action

Zinc in a voltaic cell reacts with the dilute acid and is used up even when no electricity is produced or the circuit is open. Pure zinc, however, does not react with dilute sulphuric acid, but it is costly to be used in cells. Ordinary zinc used in cells contains impurities mainly of carbon and iron. These impurities within the acid form tiny cells along with zinc particles and a chemical reaction takes place; zinc is consumed uselessly. The defect is called *local action*.

Local action can be prevented by *amalgamating* or covering zinc with a fine layer of mercury. The mercury dissolves some of the zinc but none of the impurities which remain covered. Therefore, the acid only comes into contact with pure zinc and no local cells are formed. Hence no reaction takes place when the circuit is open. In this way local action is prevented.

Polarisation

You have already noticed that when a simple cell is set up, the glow in the bulb became fainter and within a minute or two it went out. When a simple cell is used, hydrogen gas is liberated at the copper electrode and forms a fine layer on it which prevents the acid from reacting with the metal. Hydrogen does not conduct electricity and therefore weakens the current and ultimately stops it. The cell is then said to be *polarised*. This defect is called *polarisation*. Hydrogen forms a new pole between the two metals.

Simple cell: Zinc-acid-copper

Polarised cell: Zinc-acid-hydrogen-copper

The defect can be removed mechanically by wiping off the layer of hydrogen. This, however, is cumbersome and impractical. The problem can be solved chemically by adding a chemical, known as a *depolarising agent*, that either absorbs the hydrogen as is the case in the Leclanche or dry cell or substitutes it as is the case in the Daniel cell. In the Leclanche cell an oxidizing agent, manganese dioxide, is used, and in a Daniel cell a substituting agent, copper sulphate, is utilised as a depolariser.

17.3 Daniel Cell

The Daniel cell is a primary cell in which current is obtained by the conversion of chemical energy into electrical energy. It consists of a copper vessel which contains copper sulphate solution. In the copper vessel is immersed a porous pot containing dilute sulphuric acid which acts as an electrolyte. An *amalgamated* zinc rod is dipped in the acid; it serves as the negative electrode. There is a perforated shelf at the top of the copper vessel in which crystals of copper sulphate are kept to be added to the solution when needed. Its e.m.f. (electromotive force or voltage) is 1.08 volts.

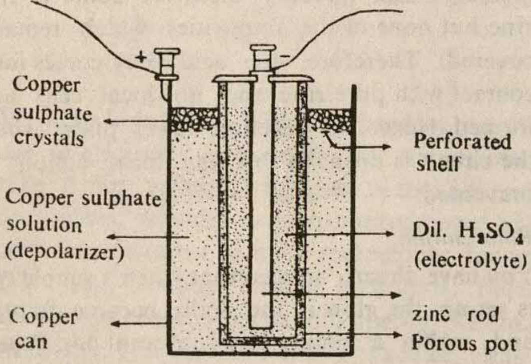


Fig. 17.3 Daniel cell

When the circuit is completed, zinc reacts with dilute acid to produce hydrogen ions which move towards the copper vessel and react with copper sulphate to give copper ions. Thus, copper deposits on the copper vessel and there is no polarisation.

$$CuSO_4 + 2H^+ \longrightarrow H_2SO_4 + Cu^{++}$$

In the outer circuit electrons flow from zinc to copper, which combine with copper ions to form copper.

$$Cu^{++} + 2e \longrightarrow Cu$$

The use of amalgamated zinc avoids local action and the use of the depolarizer, $CuSO_4$ solution, prevents polarisation. As copper sulphate is consumed so in order to maintain its strength to obtain steady e.m.f., fresh copper sulphate is added from time to time.

17.4 Leclanche Cell

The only primary cell which is still in use is of a type invented by the French scientist, Leclanche, in 1868. Its e.m.f. is 1.5 V and is used for devices where current is required intermittently, such as electric bells, telegraph and telephone circuits.

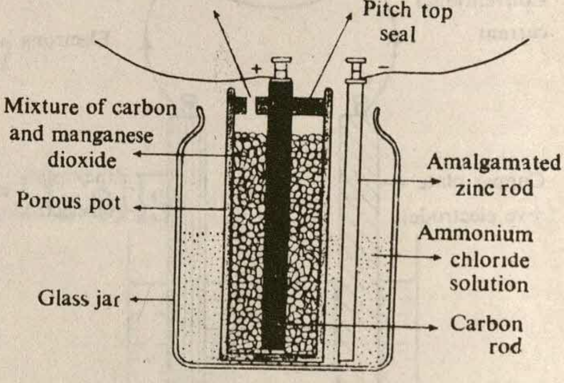

Pitch top seal
+
−
Mixture of carbon and manganese dioxide
Porous pot
Glass jar
Amalgamated zinc rod
Ammonium chloride solution
Carbon rod

Fig 17.4 Leclanche cell

It consists of a glass vessel which contains a saturated solution of ammonium chloride in which is dipped an amalgamated zinc rod and a porous pot. The conducting carbon rod is placed inside the porous pot packed with a mixture of finely divided manganese dioxide and carbon particles. The mixture acts as a depolarizer, manganese dioxide supplies the necessary oxygen to oxidize hydrogen to water and the carbon particles make the mixture conducting.

Zinc reacts with ammonium chloride solution or paste to give zinc chloride, free ammonia and hydrogen ions. Hydrogen is oxidized by MnO_2.

$$2MnO_2 + 2H^+ + 2e^- \longrightarrow Mn_2O_3 + H_2O$$

Manganous oxide thus formed combines with the oxygen of air to again get oxidized to manganese dioxide.

Manganese dioxide is usually able to oxidize hydrogen as soon as it is formed, if the reaction is slow or when small continuous current is taken from the cell. With larger currents, hydrogen forms quickly and some of it reaches carbon and starts polarisation. Current then weakens, but recovers again if the cell is disconnected to give time for the hydrogen to change into water. For this reason, Leclanche cells are used in devices where heavy currents are not needed and preferably where current is needed at intervals.

The main advantage of the Leclanche cell is that it is cheap to run and does not need much attention. All it needs is a little water once a month to make up for evaporation and new ammonium chloride solution once a year.

17.5 Dry Cell or Dry Leclanche Cell

Dry cells are used in torches, portable transistors, hearing-aid devices and many toys. A dry cell is a modified form of Leclanche cell in which the zinc container serves as the negative electrode and ammonium chloride solution is replaced by a jelly like material consisting of starch, flour and ammonium chloride (Fig. 17.5).

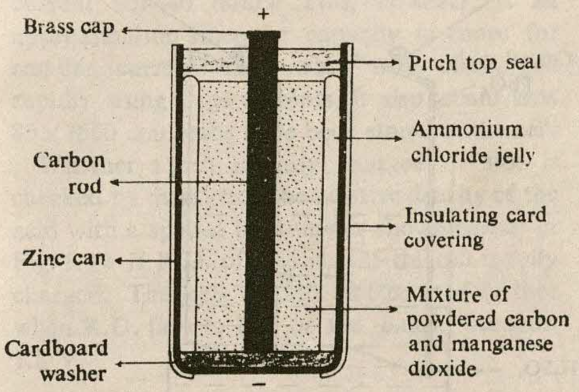


Fig. 17.5 Dry cell

The central carbon rod with a brass cap serves as a positive electrode; it is surrounded by a moist mixture of finely divided manganese dioxide and powdered carbon which acts as a depolarizer. A piece of cardboard placed at the bottom of the zinc container insulates the carbon rod from the zinc case. A layer of pitch seals the top of the cell and prevents the chemicals from drying out. The cell itself is dry from outside but its contents are kept moist or otherwise it will not work.

The e.m.f. of a dry cell is 1.5 V and its main advantage over other cells is that it is compact in size, light and portable. Local action in it is prevented by using an amalgamated zinc case and polarisation is avoided by using the mixture of manganese dioxide and carbon particles which oxidizes hydrogen into water.

17.6 Primary and Secondary Cells

In primary cells two electrodes of different metals chemically react with an electrolyte and chemical energy thus produced is converted into electrical energy to give current. The chemical reaction is irreversible and the run down cells cannot be recharged by sending current in the reverse direction through them. For example, in a Daniel or a Leclanche cell when the whole of the zinc has been used up, the cell cannot be restored to its original condition by passing current through it in the opposite direction.

There is another class of cells in which first electrical energy is stored as chemical energy by a chemical reaction by passing current through them from an external current source like a dynamo. The process is called *charging*. When a charged cell is connected to a circuit, electric current is obtained by the conversion of stored chemical energy into electrical energy by a reverse chemical reaction. Such cells are called *secondary cells*, *storage cells* or *accumulators*. Accumulators are of two types: (i) lead-acid cells, and (ii) nickle-cadmium alkaline cells. Lead accumulators are extensively used in motor-bikes, cars, buses and trucks for ignition and lighting. The main advantage of such cells is that large currents can be obtained from them. They are, however, heavy and need great attention for their maintenance.

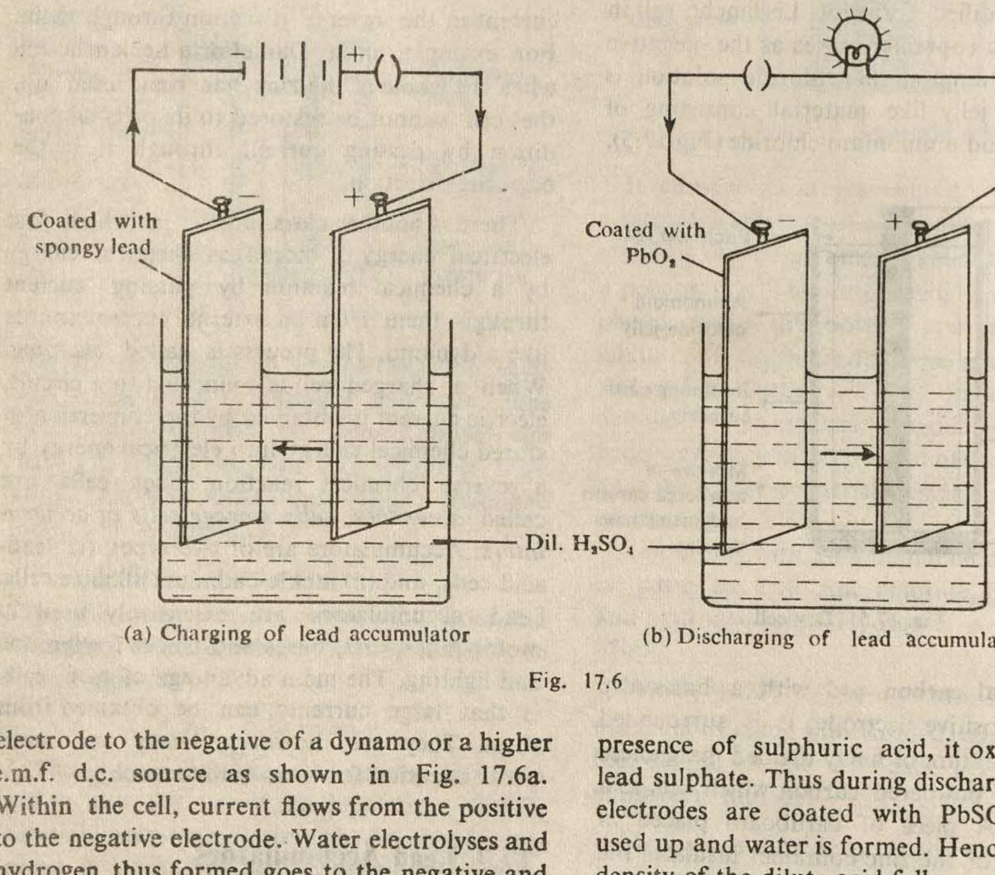
17.7 Lead Accumulators

Lead-acid accumulators are the commonest type of secondary cells. In its simplest form a lead-acid accumulator consists of two heavy grid shaped lead electrodes suspended in dilute sulphuric acid contained in a glass or perspex container.

When the cell is charged, the positive electrode gets coated with lead dioxide and the negative with spongy lead; the specific gravity of the acid rises from 1.15 to 1.25 and the e.m.f. becomes 2.1 V. On discharging, both the electrodes are coated with lead sulphate and the specific gravity of the acid falls. The cell should be recharged before the e.m.f. falls below 1.8 V, otherwise it may get permanently damaged.

Charging the Accumulator

In order to charge the accumulator, the positive electrode is joined to the positive and negative electrode to the negative of a dynamo or a higher e.m.f. d.c. source as shown in Fig. 17.6a. Within the cell, current flows from the positive to the negative electrode. Water electrolyses and hydrogen thus formed goes to the negative and oxygen to the positive electrode. At the negative electrode, hydrogen reduces lead sulphate to lead; at the positive electrode oxygen oxidizes lead sulphate to lead dioxide. At the same time, acid is set free and water is absorbed. Thus at the end of charging, the positive electrode is coated with lead dioxide and the negative with spongy lead, and the specific gravity of the solution increases.



(a) Charging of lead accumulator

(b) Discharging of lead accumulator

Fig. 17.6

Discharging the Accumulator

When current is taken from the charged accumulator by connecting it to a lamp, current flows in the outer circuit from the positive to the negative and within the cell from the negative to the positive electrode. Water gets electrolysed and hydrogen appears at the positive electrode where it reduces lead dioxide to lead sulphate in the presence of dilute sulphuric acid. Oxygen goes to the negative electrode where in the presence of sulphuric acid, it oxidizes lead to lead sulphate. Thus during discharging both the electrodes are coated with $PbSO_4$; H_2SO_4 is used up and water is formed. Hence the relative density of the dilute acid falls.

In order to obtain a large current, the internal resistance of the cell is made low by having grid shaped set of plates of as large a surface area as possible and placing them very close to each other (Fig. 17.7).

The *current carrying capacity* of an accumu-

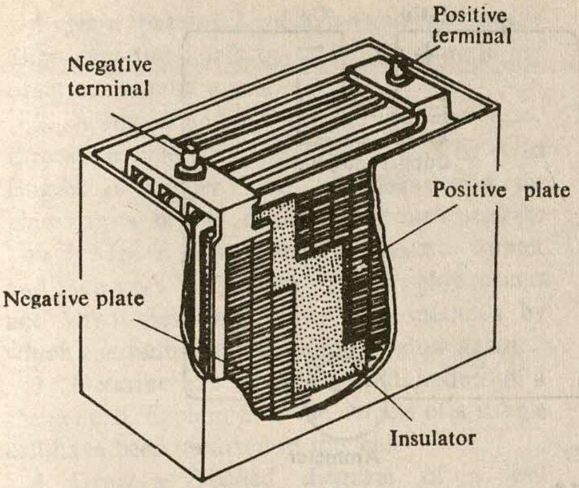


Fig. 17.7

lator is measured in ampere-hours (AH). If a battery is rated as 80 AH, this means that it will give a current of 8 A for 10 hours and a 2A current for 40 hours. This, however, is an approximation since the capacity is more for smaller currents than when it is discharged rapidly using large currents. It also means that 80 × 3600 coulombs have been stored in the cell.

Whether a cell is fully charged or not is checked by measuring the relative density of the acid with a special hydrometer shown earlier in Fig. 5.29 If R.D. of acid is 1.25 the cell is fully charged. The cell should not be used further when R.D. falls to 1.15 or the e.m.f. becomes 1.8 V.

Care and Maintenance of Lead Accumulators

1. The level of the acid in the cell should be inspected regularly and distilled water should be added from time to time to make up for any loss due to evaporation.
2. Acid should never be added except in rare cases when spillage has occured.
3. Cells should be charged regularly using the manufacturer's recommended current rating and should never be left for any length of time in a discharged condition. If the cell is left in discharged condition for long a white deposit of crystalline lead sulphate may form on the plates. Then it becomes difficult to convert the lead sulphate into lead and lead dioxide. Once this occurs, cells are said to be 'sulphated' and the only way of repair is to change the plates.
4. When not in use, they should be given 'topping' up charge at least once a month.
5. Never charge an accumulator too rapidly by sending a large current. This would cause brisk evolution of hydrogen from negative plates and oxygen from positive plates. This unnecessary 'gassing' may blow off active material from the plates.
6. Avoid over discharging and 'shorting', i.e. connecting a wire directly across the terminals. This is extremely detrimental. Such treatment causes swelling and buckling of the plates and results in the fall of the active material to the bottom as sledge.

Advantages and Disadvantages of Accumulators

The main advantage of an accumulator is that it can be discharged and recharged number of times. Even when its initial cost is very high, in the long run it is more economical than dry cells. Another advantage is that a large current for a long duration can be obtained from an accumulator as its internal resistance is low.

Its main disadvantage is that it is heavy and there is a danger of the corrosive acid spilling over. Also it requires great care for propei maintenance.

17.8 Effects of Electric Current

Activity 1. Take a 6V battery (a battery is a number of cells joined together), two ammeters (ammeter is an instrument with which current is measured in amperes), one switch, one 4 V bulb fitted in a holder, a piece of iron and a vessel containing copper sulphate solution in which two copper plates are dipped. Join them all as shown in the circuit diagram (Fig. 17.8) taking care that the positive terminal of the ammeter is joined to the positive terminal of the battery.

The positive terminal of the battery is joined to the positive terminal of one ammeter whose negative terminal is joined to one terminal of the switch or key. The other terminal of the key

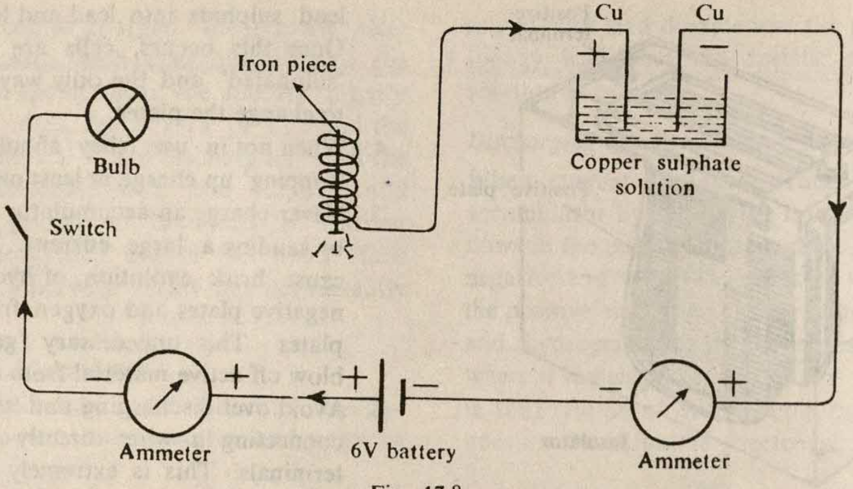


Fig. 17.8

is joined to the bulb. After the bulb, wind the connecting wire 10-12 times on an iron nail or an iron bar and then join it to the copper plate. The second copper plate is joined to the positive terminal of the other ammeter whose negative terminal is joined to the negative terminal of the battery. Such an arrangement is called a series arrangement. Place the copper plates in the copper solution taking care that they do not touch each other. Check the connection, taking care that they are tight and switch on the current. The following effects are observed:

(i) The bulb glows and its outer surface becomes hot after some time. In the bulb, part of the electrical energy being supplied is converted into heat. This is called the *heating effect* of the electric current.

(ii) Bring some smaller nails near one end of the iron piece; it attracts the iron nails showing that the piece has been magnetised on passing current in the coils wound round it. This is known as the *magnetic effect* of the current.

(iii) Pass the current for some time, say about 5 minutes and then take out the negative copper plate. Wash it under running water; it is found to be covered with a fine layer of copper. Current is responsible for the deposition of copper through a reaction. This is called the *chemical effect* of current.

Note the readings of the two ammeters. You will find that both show the same readings. Replace the 6 V battery with a 4 V battery and repeat the experiment. It is found that (i) the bulb glows less brightly, (ii) the iron piece attracts a smaller number of iron nails and (iii) the deposit of copper on the negative plate in the same time is less than before. This leads us to two important conclusions:

(1) The current is not consumed; the same current flows continuously round the circuit.

(2) The battery only supplies electrical energy and not current. When the supply of energy changed from 6 J/C to 4 J/C, less energy was available for conversion in the three effects.

QUESTIONS

1. Give a brief account of the action of a simple cell. Illustrate your answer with a diagram. Explain how the electricity passes through its electrolyte.

Explain the terms *local action* and *polarisation*. Show how these defects can be overcome in one practical form of a cell.

2. A copper and a zinc plate are connected through a small low-power torch bulb by short lengths of copper wires. On immersing the plates in a beaker of dilute sulphuric acid the bulb is seen to glow. The glow becomes fainter and then goes out. Explain why the glow occurs and why it dies away. Give two methods by which the bulb could be made to glow again.

3. Describe the structure and action of a Daniel cell. Explain how the defects of a simple cell have been removed in this cell.

4. Draw a labelled diagram of a wet Leclanche cell and explain the function of its various components.

5. Draw a labelled diagram to show the structure of a dry cell. State the source of electrical energy which a dry cell provides and explain why it is unable to maintain large currents for long periods of time.

6. Draw a labelled diagram showing the structure of lead-acid accumulator. State clearly the chemical composition of the two plates when the accumulator is:

(i) in the charged condition;

(ii) in the discharged condition.

What changes take place in the electrolyte when the accumulator is being:

(i) charged

(ii) discharged

(No chemical equations are required.)

7. Name two advantages and two disadvantages which a lead accumulator has over a Leclanche cell.

Distinguish between a primary and a secondary cell.

8. Give two precautions regarding the care of a lead-acid accumulator which is only occassionally used and two precautions which one should observe while charging the accumulator. For what purpose are the cells of the lead-acid type commonly used and why?

9. What are the effects produced by an electric current? Describe an experiment to illustrate these.

10. What do you mean by electric current?

Calculate the amount of charge that passes through a conductor when 1.5 A current flows for 4 seconds.

Distinguish between electronic and conventional current

11. Why should a naked flame be kept away from a lead-acid accumulator being charged?

12. What is meant by 'short-circuited' and 'sulphated' as applied to an acid accumulator?

18

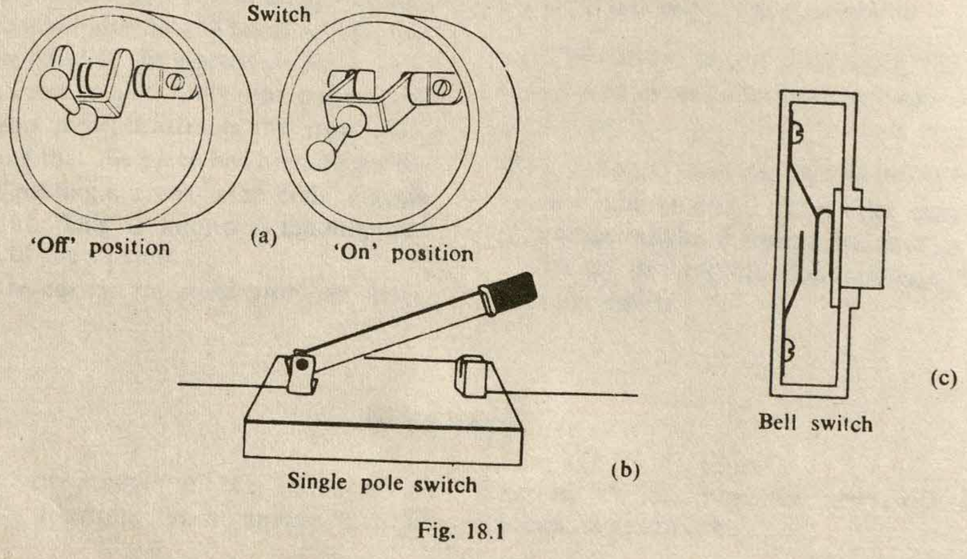
Resistance and Heat Energy

When an electric current flows through a conductor, some heat is always produced. The amount of heat produced depends upon the strength of current and also on the amount of resistance offered by the conductor to the flow of current. Let us study what is meant by resistance, how it controls current and what factors affect the amount of heat produced by current flowing through a conductor.

18.1 Resistance

Some materials conduct electricity better than others because they offer less obstruction to the flow of free electrons through them. They are said to have a low electrical resistance. **Resistance** *is the property of a substance which opposes or limits the flow of current through them and a* **resistor** *is a part or component of a circuit which is designed to possess a certain resistance.*

Pure copper is a very good conductor of electricity and is used in cables or wires which can carry electrical energy from one place to another without much loss. Certain *alloys* of copper with other metals offer high resistance to the flow of current through them, in overcoming which heat is produced. *Constantan* contains 60% copper and 40% nickle, and *manganin* is a mixture of 84% copper, 12% manganese and 4% nickle. The resistance they



'Off' position (a) 'On' position

Single pole switch (b)

Bell switch (c)

Fig. 18.1

offer is around 25 times that of copper of the same dimensions. They are used in the manufacture of quality resistors. *Nichrome* which contains 80% nickle and 20% chromium offers 60 times the resistance of copper of the same dimensions and it also resists oxidation when red hot. It is therefore used in heating elements of electric stoves and irons.

Air at normal pressure offers very high resistance to the flow of current. Thus when an air gap is introduced in a circuit, the current stops flowing. This is the principle of the 'keys' and switches (Fig. 18.1) used to turn off or on the current in a circuit.

The Rheostat

This consists of a coil of resistance wire with a sliding contact that can be moved along the wire (Fig. 18.2a). As the contact is moved to the right, current flows through a greater length of the resistance wire. This increases the resistance and reduces the current of the circuit in which it is inserted.

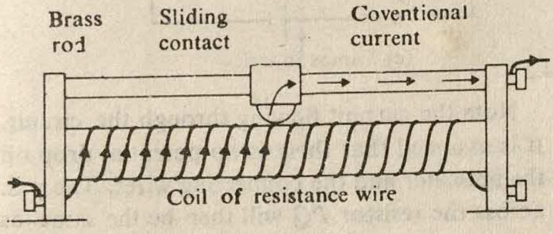


Fig. 18.2(a) A rheostat

As the contact is moved to the left, current flows through a smaller length of the resistance wire. The resistance decreases and the current increases.

18.2 Electric Circuit

When the terminals of a cell are joined to a resistor, say a lamp, an electric circuit is formed (Fig. 18.2b). When they are connected correctly, the bulb glows and the circuit is said to be a **complete circuit**. If any one terminal is left unconnected, the bulb will not glow.

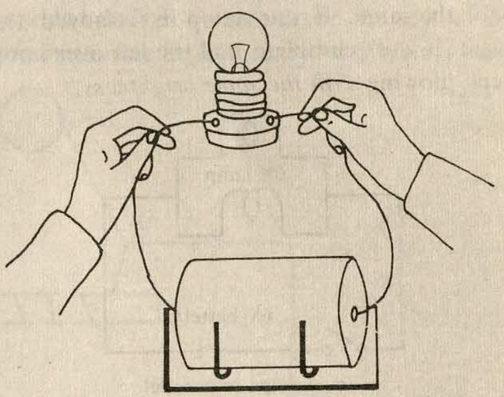


Fig. 18.2(b) A simple electric circuit

Usually a key or a **switch** is introduced in a circuit to complete or break it. Components such as the bulb, wires, cell and key are known as the **elements** of a circuit. Fig. 18.2c shows the

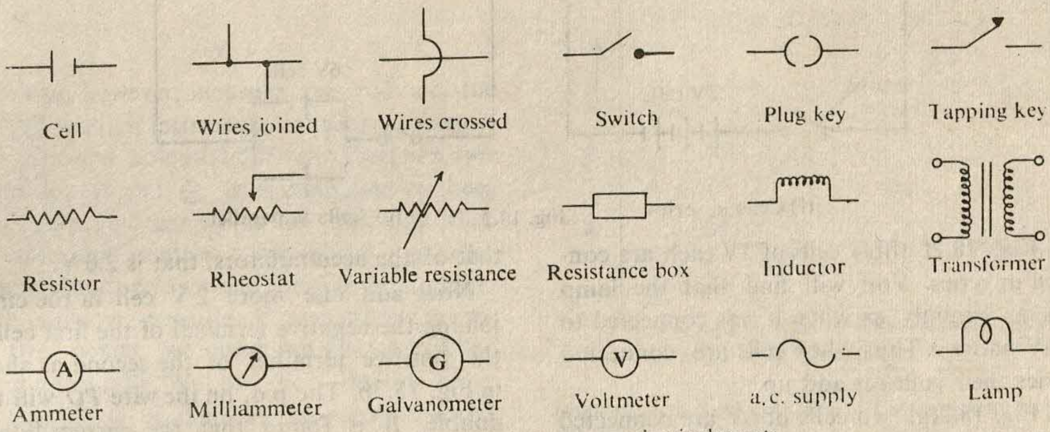
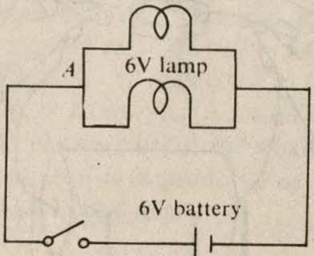


Fig. 18.2c Symbols for common circuit elements

circuit symbols of various elements which you will be using.

A 6V lamp operates normally using a 6V battery. But how can you operate two or more such lamps normally from this source of energy? And how can a number of 2V cells be used to normally operate a 6V lamp? These problems can be solved by using the circuit elements in **series** or **parallel combinations**.

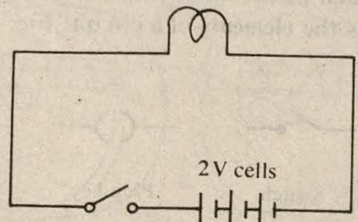
Let us consider the parallel arrangement of lamps shown in Fig. 18.2(d). In this arrangement the current at *A* divides and goes through each lamp. Thus the current throughout the circuit is not the same. If one lamp is removed the circuit is still complete and the left over lamp keeps glowing *with the same brightness*.



(d) Lamps in parallel

Fig. 18.2

When the lamps are connected in series (Fig. 18.2e) each lamp will glow less brightly. In this case the current throughout the circuit is the same.



(f) Cells in series

Fig. 18.2

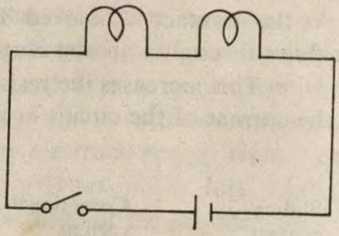
In Fig. 18.2f three cells of 2V each are connected in series. You will find that the lamp glows as brightly as when it was connected to one 6V battery. Thus when cells are connected in series their voltages add up.

In Fig. 18.2(g) two cells of 6V are connected in parallel. The lamp will be found to glow with the same brightness as if it were connected to a single 6V cell. Thus voltages of cells in parallel remain the same.

18.3 Ohm's Law

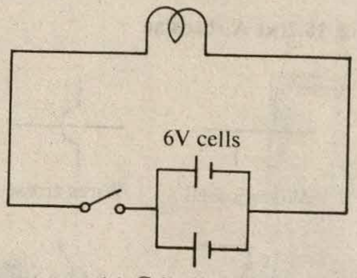
In the year 1826, George Simon Ohm, a German school teacher, experimentally established a relation between current *I*, p.d. *V* and the resistance *R* of a circuit.

Activity 1. Wind a 20 cm long and 28 SWG nichrome resistance wire round a wooden rod or a pencil and connect it in series with an ammeter, switch and a 2 V cell as shown in Fig. 18.3



(e) Lamps in series

Note the current flowing through the circuit. It is assumed that there is no potential drop on the ammeter and the connecting wires. The p.d. across the resistor *PQ* will then be the same as that of the accumulators, that is 2.0 V.



(g) Cells in parallel

Now add one more 2 V cell in the circuit joining the negative terminal of the first cell to the positive terminal of the second as shown in Fig. 18.3b. The p.d. on the wire *PQ* will now double. It is found that the current flowing through *PQ* is also doubled. With three cells

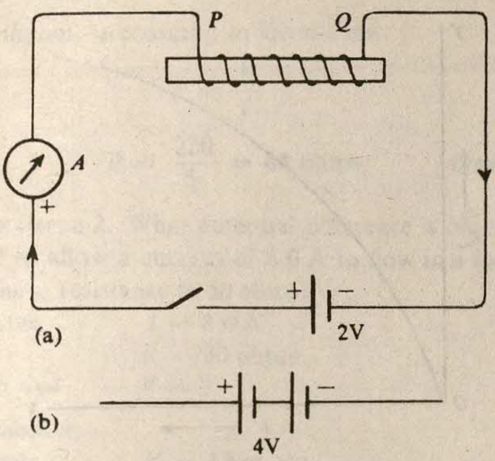


Fig. 18.3

in the circuit the current is trebled. This shows that current *I* is directly proportional to the p.d. *V*.

$$I \propto V$$

We can, however, measure the p.d. on the wire *PQ* with an instrument called a voltmeter. As it measures potential difference between two points say *P* and *Q*, it is connected to these points only. In other words, we may say that the voltmeter is always connected in parallel to the resistor across which the p.d. is required. As we can now measure *V* accurately across any two points, we need not change p.d. by adding more cells. We can now do the same by introducing a rheostat as shown in the Fig. 18.4.

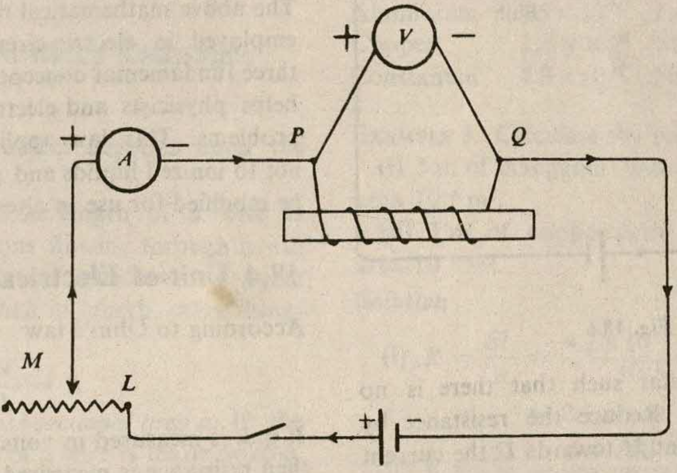


Fig. 18.4

Activity 2. Connect a lead accumulator, a key, a rheostat, an ammeter and the resistor *PQ* in series as shown in Fig. 18.4. Join the voltmeter in parallel to *PQ*. Switch on the current and note the readings of the ammeter and voltmeter. Take care that current enters the ammeter and the voltmeter to give positive deflection.

Switch off the current. Alter the position of the rheostat and repeat the experiment at least 6 times. Plot a graph of *V* against *I*. It is a straight line passing through the origin as shown in Fig. 18.5.

The graph line passes through the origin provided there is no zero error in any of the two measuring instruments and the scale starts from 0.0 on both the axes. It is essential to pass the current for a short duration by using a key

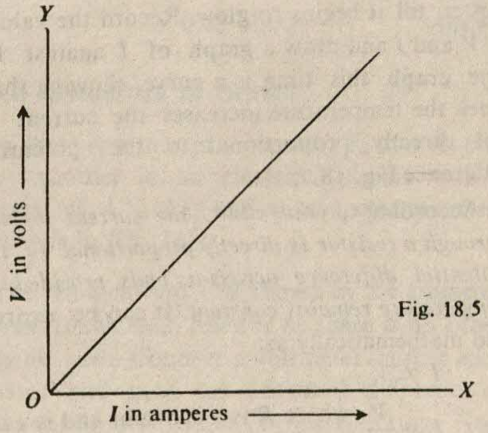


Fig. 18.5

to avoid heating. Interchange the connections of the two terminals of the ammeter and voltmeter if on switching on the current any of the two gives a deflection on the wrong side of zero. Make sure the connections are tight; loose connections give wrong values.

Activity 3. Repeat the above experiment by using a torch bulb fitted in the holder instead of the nichrome wire *PQ* as shown in Fig. 18.6

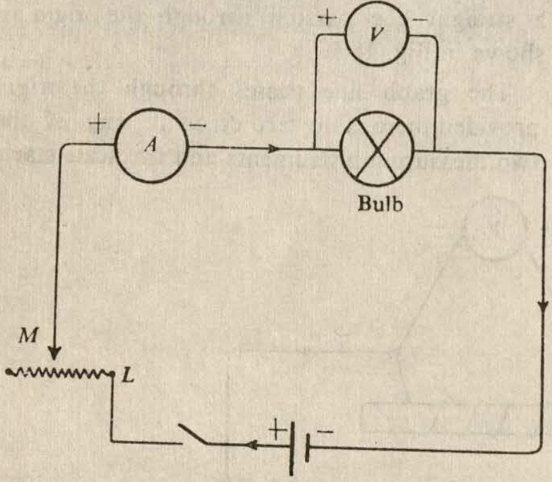


Fig. 18.6

Adjust the rheostat such that there is no glow in the bulb. Reduce the resistance by moving contact point *M* towards *L*; the current increases and the bulb becomes hotter and hotter till it begins to glow. Record the values of *V* and *I* and draw a graph of *I* against *V*. The graph this time is a curve, showing that when the temperature increases the current is not directly proportional to the potential difference Fig. 18.7.

According to *Ohm's law, the current flowing through a resistor is directly proportional to the potential difference across its ends, provided the temperature remains constant.* It can be expressed mathematically as:

$$I \propto V$$

or $I = \frac{V}{R}$ where *R* is a constant and is called the resistance of the resistor

or $\frac{V}{I} = R$

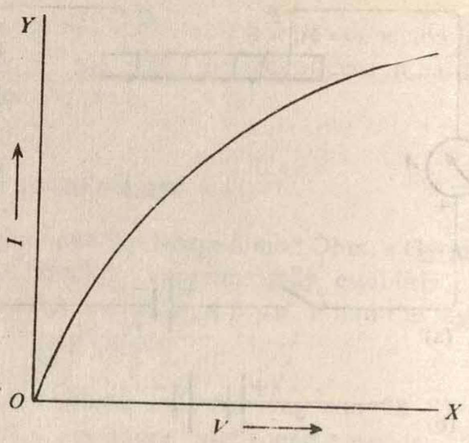


Fig. 18.7

The above mathematical relation is more often employed in electric circuits because it relates three fundamental concepts in electricity and helps physicists and electricians to solve many problems. This law applies only to solids and not to ionized liquids and gases and needs to be modified for use in alternating currents.

18.4 Unit of Electrical Resistance

According to Ohm's law

$$R = \frac{V}{I}$$

If p.d. is measured in volts, current in amperes, then resistance is measured in ohms.

$$R \text{ (in ohms)} = \frac{V\text{(in volts)}}{I\text{(in amperes)}}$$

If $V = 1$ volt, $I = 1$ ampere, then the resistance of the conductor is 1 ohm represented symbolically by the symbol Ω which is the Greek letter *Omega*.

The resistance of a conductor is 1 **ohm** *if it permits 1 ampere current to exist when a potential difference of 1 volt is maintained across it.*

EXAMPLE 1. A bathroom heater draws 5 A when operating from a 220 V d.c. line. What is its resistance while operating?

Given $I = 5$ A

$V = 220$ V

To find $R = ?$

Solution According to Ohm's law:

$$R = \frac{V}{I}$$

$$\therefore \quad R = \frac{220}{5} = 44 \text{ ohms} \qquad \textit{Answer}$$

EXAMPLE 2. What potential difference is required to allow a current of 8.0 A to flow in a load whose resistance is 50 ohms?

Given $I = 8.0$ A
$R = 50$ ohms
To find $V = ?$

Solution
Since $V = IR$
$\therefore$ $V = 8 \times 50 = 400$ volts *Answer*

18.5 Factors upon which Resistance Depends

The resistance of an object depends upon the following factors:

1. *Length l.* When the length of a wire is made double electrons flowing through it will encounter twice as much resistance as going through the wire of half its length, other things remaining same.

$$R \propto l$$

2. *Thickness or cross-sectional area a.* If the cross-sectional area of a wire is made double, other things remaining same, it will have twice the number of free electrons and hence its resistance will become one-half of what it was before.

$$R \propto \frac{1}{a}$$

Hence thinner the wire, more is the resistance.

3. *Nature of the material.* Some materials have more free electrons than others and hence have less resistance.

Combining factors (1) and (2)

$$R \propto \frac{1}{a}$$

or $R = \frac{Sl}{a}$ where S is a constant called resistivity constant or specific resistance. It depends upon the nature of the material.

$$S = \frac{Ra}{l}$$

If $a = 1 \text{ m}^2$ and $l = 1$ m then

$$S = \frac{R(\text{in ohms}) \times 1 \text{ m}^2}{1 \text{ m}}$$
$$= R \text{ ohm metre}$$

Resistivity or specific resistance *of a material is defined as the resistance of a conductor of that material of length 1 m and cross-sectional area 1 m².* It is measured in ohm metre or Ω m.

It has nothing to do with the size and shape of the material and depends only on its nature. The following table gives the resistivities of some common materials in Ω m at 0°C.

Aluminium	2.5×10^{-8}	Tungsten	4.9×10^{-8}
Copper	1.6×10^{-8}	Manganin	4.2×10^{-7}
Constantan	4.8×10^{-7}	Nichrome	1.03×10^{-6}

EXAMPLE 3. Calculate the resistance of

(i) 5 m of manganin wire of cross-sectional area 10^{-6} m².

(ii) 5 m of copper wire of cross-sectional area 10^{-6} m².

Solution

$$\text{(i)} \quad R = \frac{Sl}{a} = \frac{4.2 \times 10^{-7} \times 5}{10^{-6}} = 21 \times 10^{-1}$$
$$= 2.1 \text{ ohms} \qquad \textit{Answer}$$

$$\text{(ii)} \quad R = \frac{Sl}{a} = \frac{1.6 \times 10^{-8} \times 5}{10^{-6}} = 8 \times 10^{-2}$$
$$= 0.08 \text{ ohms} \qquad \textit{Answer}$$

18.6 Resistors in Series

Join three resistors of values R_1, R_2 and R_3 one after another in an electrical circuit with a battery of 4 V, key and an ammeter in series, as shown in Fig. 18.8.

The same current I as shown by the ammeter flows through each resistor as there is no other possible path. Connect a voltmeter across each resistor and note the potential difference or potential drop V_1, V_2, V_3 on each in turn. Now connect the voltmeter across P and Q which are the terminals of the *equivalent resistance* and note the total potential difference V. It is

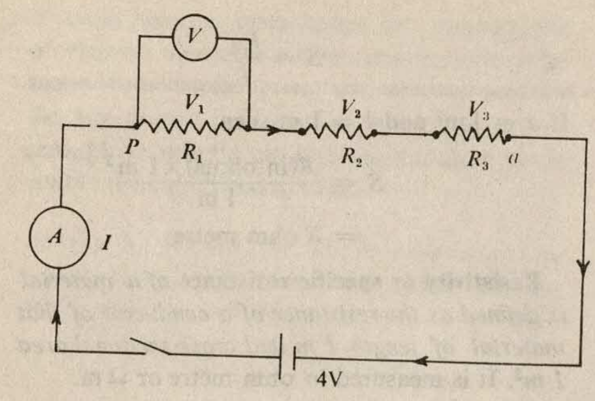


Fig. 18.8

found that

$$V = V_1 + V_2 + V_3$$

Equivalent resistance is that single resistance whose effect is the same as the combined effect of all the individual resistances taken together. Let it be R. According to Ohm's law:

$$V_1 = IR_1; \quad V_2 = IR_2; \quad V_3 = IR_3$$

and $$V = IR$$

as $$V = V_1 + V_2 + V_3$$

$$\therefore \quad IR = IR_1 + IR_2 + IR_3$$

$$= I(R_1 + R_2 + R_3)$$

Hence $$R = R_1 + R_2 + R_3$$

This is called the *law of resistances in series*, according to which the equivalent resistance of a number of resistances in series is equal to the sum of individual resistances taken together. Remember that in series the total potential drop is equal to the sum of the potential drops on individual resistances, but the current is same in all.

18.7 Resistors in Parallel

Connect three resistors of value R_1, R_2 and R_3 in such a way that their one ends are joined together at one point P and the other ends are joined at another point Q. Such an arrangement is called *resistors in parallel* and the two points P and Q act as the terminals of the equivalent resistor. Let its value be R.

Connect ammeters, a switch and a 2 V cell as shown in Fig. 18.9. As all the resistances are connected between the same points P and Q, hence the potential drop V on each is the same as that on the equivalent resistance.

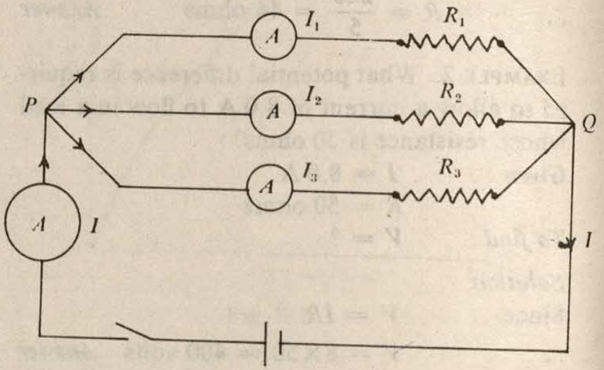


Fig. 18.9

Check up the readings of ammeters. You will find that total current I divides among the various resistances and is equal to the sum of the currents flowing through individual resistances,

i.e. $$I = I_1 + I_2 + I_3$$

According to Ohm's law:

$$I_1 = \frac{V}{R_1}; \quad I_2 = \frac{V}{R_2}; \quad I_3 = \frac{V}{R_3}$$

and $$I = \frac{V}{R}$$

as $$I = I_1 + I_2 + I_3$$

$$\therefore \quad \frac{V}{R} = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3}$$

or $$V\left(\frac{1}{R}\right) = V\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right)$$

Hence $$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

This is the *law of resistances in parallel* which states that reciprocal of the equivalent resistance is equal to the sum of the reciprocals of the individual resistances.

Remember that in parallel, p.d. is same across all resistances but current divides, and the total current is the sum of individual currents flowing through each resistor.

Example 4. Resistors of 2, 3 and 4 ohms are connected in (i) series and (ii) parallel. Calculate equivalent resistance in each case.

Given $R_1 = 2$ ohms

$R_2 = 3$ ohms

$R_3 = 4$ ohms

Solution

(i) In series $R = R_1 + R_2 + R_3$

$\therefore$ $R = 2 + 3 + 4 = 9$ ohms

Answer

(ii) In parallel $\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$

$$\therefore \frac{1}{R} = \frac{1}{2} + \frac{1}{3} + \frac{1}{4}$$

$$= \frac{6 + 4 + 3}{12} = \frac{13}{12}$$

Hence $R = \frac{12}{13}$ ohms *Answer*

EXAMPLE 5. A cell of 2 V is connected in series with two resistors of 2 and 4 ohms. Calculate (i) current in the circuit; (ii) potential drop on each resistor.

Given $R_1 = 2$ ohms

$R_2 = 4$ ohms

$V = 2$ volts

To find $I = ?$

$V_1 = ?$

$V_2 = ?$

Solution

In series $R = R_1 + R_2$

$\therefore$ $R = 2 + 4 = 6$ ohms

$I = \frac{V}{R} = \frac{2}{6} = 0.33\text{A}$ *Answer*

Since $V_1 = IR_1$

$\therefore$ $V_1 = 0.33 \times 2 = 0.66$ volts

Also $V_2 = I\,R_2 = 0.33 \times 4 = 1.32$ volts *Answer*

EXAMPLE 6. If two resistors of 3 and 6 ohms are connected in parallel with a 2 V battery, calculate (i) the total current in the circuit (ii) current in each resistor:

Given $R_1 = 3$ ohms

$R_2 = 6$ ohms

$V = 2$ volts

To find I, I_1 and I_2

Solution

The equivalent resistance in parallel is

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$$

$$\therefore \frac{1}{R} = \frac{1}{3} + \frac{1}{6} = \frac{2 + 1}{6}$$

$$= \frac{3}{6} = \frac{1}{2}$$

Hence $R = 2$ ohms

According to Ohm's law:

$$I = \frac{V}{R}$$

$\therefore$ $I = \frac{2}{2} = 1.0\,A$ *Answer*

Current in 3 Ω resistor $I_1 = \frac{V}{R_1} = \frac{2}{3} = 0.67A$

Answer

Current in 6 Ω resistor $I_2 = \frac{2}{6} = \frac{1}{3} = 0.33A$

Answer

EXAMPLE 7. In the circuit shown in the Fig. 18.10, calculate

(i) current in 2 ohms resistor;

(ii) potential difference across 2 ohm resistor;

(iii) potential difference across 5 ohm resistor;

(iv) current in 10 ohm resistor.

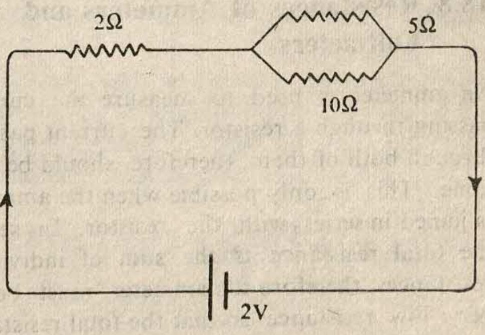


Fig. 18.10

Solution

Let the resistance of parallel combination be X.

then $\frac{1}{X} = \frac{1}{R_1} + \frac{1}{R_2} = \frac{1}{5} + \frac{1}{10}$

$$= \frac{2+1}{10} = \frac{3}{10}$$

$$\therefore \quad X = \frac{10}{3} \text{ ohms}$$

Total resistance of the circuit $R = X +$ resistance in series

$$= \frac{10}{3} + 2 = \frac{16}{3} \text{ ohms}$$

(i) Total current $I = \frac{V}{R} = \frac{2 \times 3}{16} = \frac{3}{8}$ A

Hence current in 2 ohm resistor

$$= \frac{3}{8} = 0.375 \text{ A}$$ *Answer*

(ii) Potential difference across 2 ohm resistor

$$= IR = \frac{3}{8} \times 2 = 0.75 \text{ volts}$$ *Answer*

(iii) Potential difference arross 5 ohm and 10 ohm resistors is the same as across the parallel combination of 5 and 10 ohms

$$= I \times X = \frac{3}{8} \times \frac{10}{3} = \frac{5}{4}$$
$$= 1.25 \text{ volts}$$ *Answer*

(iv) Current in 10 ohm resistor $= \frac{\text{p.d.}}{\text{resistance}}$

$$= \frac{1.25}{10} = 0.125\text{A}$$

18.8 Resistances of Ammeters and Voltmeters

An ammeter is used to measure the current passing through a resistor. The current passing through both of them, therefore, should be the same. This is only possible when the ammeter is joined in series with the resistor. In series, the total resistance is the sum of individual resistances, therefore the ammeter must be of very low resistance so that the total resistance and thereby the current almost remains the same.

As a voltmeter is used to measure p.d. across a cell or a resistor, its two terminals should be joined to the two poles of the cell or the two ends of the resistor. Hence, it is always connected in parallel. Since it is connected in parallel its resistance should be very high so that the effective resistance of the circuit remains unchanged and thereby current and p.d. remain the same.

Thus, it is clear that while an ammeter must be of very low resistance, the voltmeter must be of very high resistance.

18.9 Electromotive Force and Internal Resistance of a Cell

When the terminals of a cell are joined to an external resistance, current or charge does not only flow through the external resistance but also through the solids or liquids that constitute the cell. These materials also offer resistance to the current, particularly in small cells.

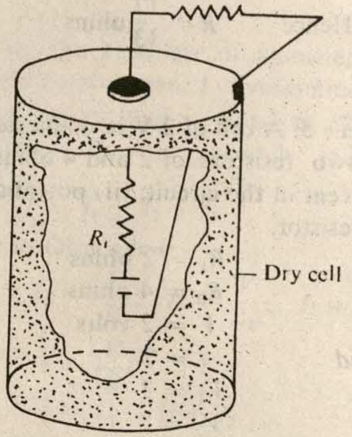


Fig. 18.11 In the dry cell internal resistance is shown as a small resistor R_i

Let the external resistance in a circuit be R and the current flowing through the circuit be I. Then

P.D. across external resistance $(V) = IR$

Pot. drop within the cell $(e) \quad = IR_i$

Total potential difference E produced due to the chemical action of the cell is given by

$$E = V + e$$
$$= IR + IR_i$$

or

$$E - V = IR_i$$

$$R_i = \frac{E-V}{I}$$

$$= \frac{(E-V)R}{V}$$

E is known as the **electromotive force** or **e.m.f.** of the cell. Hence **e.m.f.** *is the total potential difference produced by the chemical action of the cell and is equal to potential difference across the terminals of the cell when the external resistance is very high as compared to the internal resistance of the cell.* In such a case the internal voltage drop is very small and can be neglected.

If a voltmeter is connected across a cell, its reading gives the e.m.f. of the cell as the voltmeter is a very high resistance instrument. If, however, the voltmeter is connected across a resistance as shown in Fig. 18.12b, the reading will give V and not E. Using the two readings V and E we can calculate the internal resistance of the cell using the formula

$$R_i = \frac{(E - V)R}{V}$$

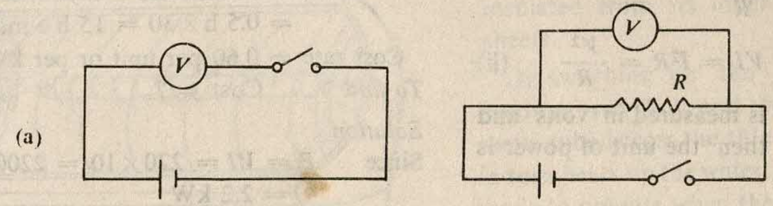
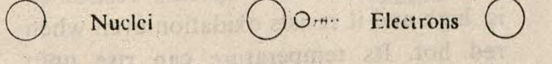


Fig. 18.12

18.10 Electrical Heating

Heat energy is produced whenever an electric current flows through a wire. As the electrons of the current flow into the metal wire, they collide with the atoms of the metal. In each collision the electrons lose some of their kinetic energy which is taken up by the atoms and they begin to vibrate faster. Their mean kinetic energy or temperature therefore increases.



Movement of electrons through metal wire
Fig. 18.13

The total amount of heat produced depends upon:

(i) *Resistance*. Higher the resistance, there are more obstacles for the electron to collide with and the heat produced is greater.

(ii) *Current*. If the current is higher, there are more electrons to collide with the obstacles and more is the heat produced.

(iii) *Time*. If current flows for a longer time more collisions take place and the heat produced is more.

Let us determine the exact relationship between current, potential difference, resistance and the heat produced.

18.11 Electrical Energy and Power

Suppose on applying a potential difference of V volts across a conductor of R ohms, a current of I amperes flows through it. Let the amount of charge flowing be Q coulombs in t seconds. You know that when a charge flows through a conductor, heat is always produced because work is done in overcoming the resistance. You have learnt that work done per coulomb is equal to potential difference in volts, that is,

$$\text{P.D. in volts} = \frac{\text{work done in joules}}{\text{charge in coulombs}}$$

or $$V = \frac{E}{Q}$$

or $$E(\text{joules}) = V(\text{volts}) \times Q(\text{coulombs})$$

You have learnt that current in amperes is equal to amount of charge that flows in one second in coulombs.

$$I = \frac{Q}{t}$$

$$\therefore \quad Q = It$$

As $E = VQ$

∴ $E = VIt$

As $V = IR$

∴ $E = I^2Rt$

Also $I = \frac{V}{R}$

∴ $E = \frac{V^2}{R^2} \times R \times t = \frac{V^2}{R} t$

Hence $E = VIt = \frac{V^2}{R} t = I^2Rt$ (i)

You know that power is the rate of doing work.

$$\text{Power} = \frac{\text{work done}}{\text{time}} = \frac{\text{energy}}{\text{time}}$$

∴ $\text{Power} = \frac{VIt}{t} = Vt$

$= I^2R$

$= \frac{V^2}{R}$

Hence $P = VI = I^2R = \frac{V^2}{R}$ (ii)

If potential difference is measured in volts and current in amperes, then the unit of power is volt-ampere or *watt*.

1 watt = 1 volt × 1 ampere

Electrical energy can be expressed in watt-second or joules.

1 joule = 1 watt × 1 second

In today's energy market, joule is a very small unit indeed. Energy is therefore usually measured in watt-hour or kilowatt-hour (kWh)

1 kWh = 1 kW × 1 hour

= 1000 W × 3600 seconds

= 3,600,000 watt-second or joules

EXAMPLE 8. An electric heater is rated 2 kW and 220 volts. Calculate:

(i) the current flowing through it;

(ii) resistance of heater in ohms:

(iii) energy consumed in 30 minutes.

Given $P = 2$ kW = 2000 W

$V = 220$ volts

$t = 30$ minutes = 0.5 h

To find $I = ?$

$R = ?$

$E = ?$

Solution

Since $P = VI$

∴ $I = \frac{P}{V} = \frac{2000}{220} = 9.09\text{A}$ *Answer*

As $R = \frac{V}{I} = \frac{220 \times 220}{2000} = 24.2$ ohm *Answer*

As $E = P \times t$

∴ E in kWh = 2 kW × 0.5 h

= 1 kWh *Answer*

= 3,600,000 J *Answer*

EXAMPLE 9. An electric bathroom heater uses 10 amperes at 220 volts. Find its power. If the cost of electricity is 60 paise per unit, find the cost of running it for 30 minutes each day in a month of 30 days.

Given $I = 10$ amperes

$V = 220$ volts

$t = 30$ minutes a day = 0.5 h a day

= 0.5 h × 30 = 15 h a month

Cost rate = 0.60 per unit or per kWh

To find Cost = ?

Solution

Since $P = VI = 220 \times 10 = 2200$ W

= 2.2 kW

$E = P \times t$

= 2.2 kW × 15 h = 33.0 kWh

Cost = 33 × 0.6

= 19.8

Cost = Rs. 19.80 *Answer*

18.12 Electric Heating Devices

The heating effect, due to an electric current, is used in a large number of electrical appliances such as electric room heaters, electric fires, kettles, immersion heaters, toasters, cookers and electric irons. All heating appliances consist primarily of two parts:

(i) A resistor called *filament* which is a coiled length of nichrome wire of suitable length. Nichrome is an alloy of 60% nickle and 40% chromium whose specific resistance is high and it resists oxidation even when red hot. Its temperature can rise upto 900°C.

(ii) The insulating base of fire-clay, mica, silica or asbestos in which the filament is embedded. As the flow of current through human body is highly dangerous and may cause even death, proper care is taken not only to insulate it from the filament but also to earth it so that if per chance leakage occurs, charge flows to the earth instead of the human body. The above materials are not only insulating but are also able to withstand high temperature of the filament.

Room Heaters

Room heaters consist of a long nichrome wire wound into a long coil around a fire-clay rod. It has a shining metal surface behind it to reflect back the heat radiations (Fig. 18.14).

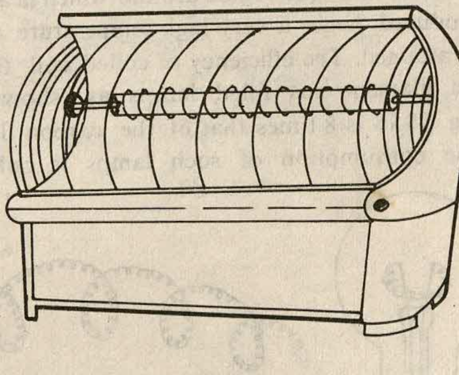


Fig. 18.14 heater

Some electric heaters have even two or three filaments wound on separate fire-clay bars. They are connected in parallel so that in each 220 volt may act and each has its own switch, so that one, two or three bars can be used as required.

Hot-plates

There are two types of hot-plates as shown in Fig. 18.15. One is a perfectly flat hot-plate which makes a good contact with a flat-bottomed sauce pan which receives heat mainly by conduction. The other type has a heating element wound inside tubular metal spirals. These are insulated from each other by mica. These heat the sauce-pan by radiation and not by conduction; they can even be made red hot.

Electric Kettle

The heating element consists of a fine nichrome wire wound on mica as shown in Fig. 18.16. The element is sealed inside a metal tube and is insulated from its inner walls by thin mica sheets.

On switching 'on' the current, the element becomes red hot and conducts heat to the metal tube across the thin mica insulation and in turn heats up the water. Kettles should only be made to operate when the element is immersed under a liquid otherwise overheating may burn the element and damage the kettle. Some kettles are provided with bimetallic strip thermostats which automatically switches off the current above a certain safe temperature and switches 'on' on cooling.

Electric Iron

The electric iron works in the same way as the

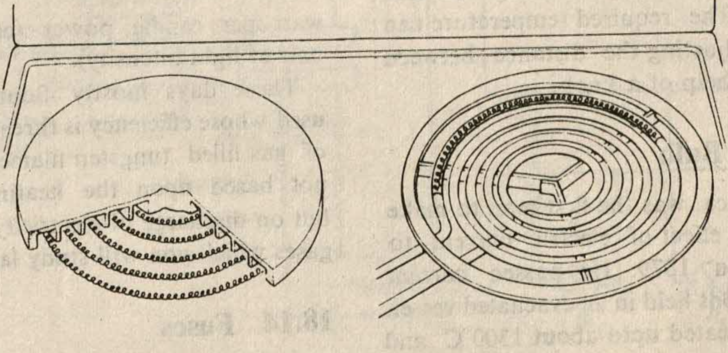


Fig. 18.15 Hot plates

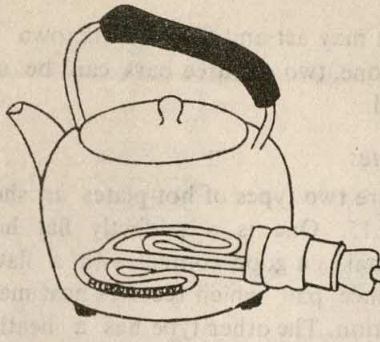


Fig. 18.16 Electric kettle

electric kettle. The element is wound into a strip of mica and is insulated from top and bottom by two other sheets of mica (Fig.18.17). An asbestos sheet is placed on the top to act as heat insulator. On it a heavy metal sheet is placed to press it down. The whole arrangement is clamped tightly onto a thick polished iron sole plate.

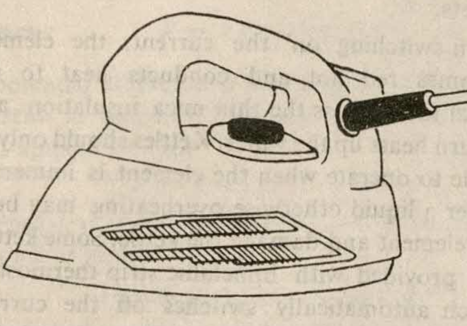


Fig. 18.17 Electric iron

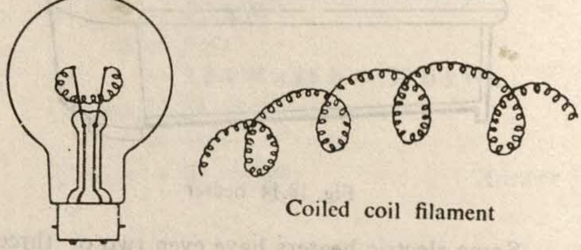
A bimetallic strip is fitted onto the iron to act as a thermostat for keeping the temperature constant by automatically switching 'on' and 'off' the current. The required temperature can be obtained by adjusting the distance between contacts with the help of a knob.

18.13 Electric Bulb

Edison in America was the first man to make use of the heating effect of electric current to produce light in 1879. He passed current through carbon rods held in an evacuated vessel. The carbon was heated upto about 1300°C and emitted light. Carbon melts at 1750°C and in vacuum because of the absence of air it does not burn. However, as a lot of electrical energy was wasted as heat, the efficiency of carbon lamps was very low.

In 1907, the carbon filament was replaced by a tungsten filament whose melting point is 3400°C. It can, therefore, safely run at a temperature in the region of 2500-2700°C. The efficiency of such lamps is about 4 times that of carbon lamps. There was a tendency of the tungsten filament to evaporate off and this limited its life.

In 1913, an inert gas like nitrogen or argon was introduced in the bulb at a low pressure. This prevented the metal from evaporating. The loss of heat by convection was reduced by coiling the filament. In about 1930, the coiled filament was replaced by a coiled coil filament which reduced the region around which heat was produced, hence a very high temperature could be attained. The efficiency of coiled coil tungsten filament gas filled lamps as shown in Fig. 18.18 is 8 times that of the carbon lamp. The consumption of such lamps is only 0.5 watt per candle power (candle power is the unit of light intensity).



Coiled gas-filled tungsten lamp

Coiled coil filament

Fig. 18.18

These days mostly flourescent tubes are used whose efficiency is three times the efficiency of gas filled tungsten filament lamps. They are not based upon the heating effect of current but on discharge of electricity through rarefied gases which you will study later on.

18.14 Fuses

An appliance is designed to take a certain current. If per chance due to 'short circuiting' or some other reason the current becomes very high, it is likely, to damage the appliance and the electric wiring may catch fire. To avoid this risk a safety device called *fuse* is used in series with the circuit.

Fuse is a short piece of wire of a low melting point material which is connected in series and melts when the current rises above the safe limit. This breaks the circuit and switches off the current.

Fig. 18.19a shows the type of fuse that is used in the main fuse box of the house. A melted piece of fuse wire can be replaced by fastening a new piece between the contacts. Fig. 18.19b shows a cartridge-type fuse. When the wire melts in this type of fuse, the whole cartridge has to be replaced. The circuit symbol of the fuse is as shown in Fig. 18.19c.

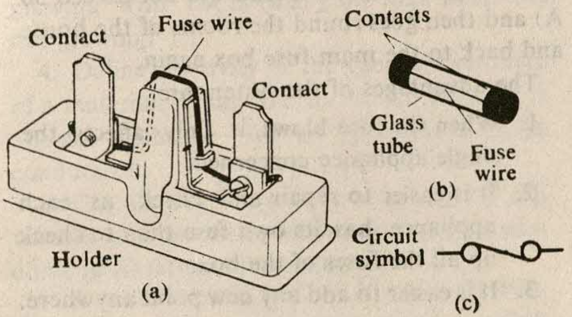


Fig. 18.19

Fuse wires are of different current-carrying capacities. An electric kettle of 2 kW will take $\frac{2000}{220} \simeq$ 9A current. A thick fuse wire rated 10 A must be used. For electric lighting, suppose 8 lamps of 60 W each are used in a house. They will take a current of $\frac{60 \times 8}{220} \approx$ 2.2 A. A thin fuse wire of 5 A should be used.

18.15 Domestic Wiring

In domestic wiring, three cored cables are used. The **live** wire coloured red brings in the electric current, the return wire often called **neutral** is coloured black and the **Earth** wire is green. In order to avoid too much complication in circuit diagrams the earth wire is omitted; it is joined to the third pin at each socket.

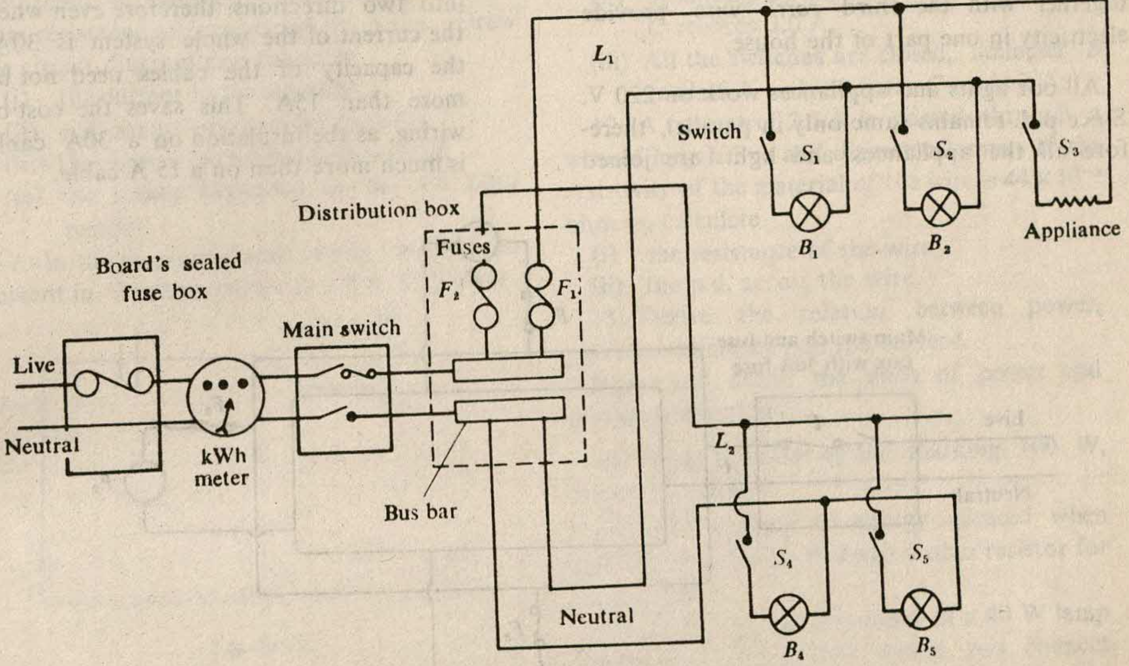


Fig. 18.20 Domestic wiring

From the power house electricity is supplied to your house by either overhead wires or underground cable. The electricity first goes to the Electricity Board's sealed fuse box which has a 60 ampere fuse inside it through which the *live* lead passes. If something goes wrong seriously in the internal wiring system, this fuse goes off. This would protect the rest of the installations and ensures that the supply to the neighbouring houses does not fail as well. The seal of this box can be broken by the Board's people only and they alone are allowed to repair it.

The leads then pass through a kWh meter which records the amount of electricity used. They then go to the main switch. When switched off none of the appliances or lights in the house will work at all. It is advised that when a house is to be kept vacant for a long period, the main switch should be turned off.

The leads from the main switch then enter the distribution box, where each is connected to a copper bar called *bus bar*.

From the bus bars, leads go off to all parts of the house, the *live* leads pass through suitable fuses. Then the live and the neutral leads together with the third *earth* wire provide electricity in one part of the house.

All our lights and appliances work on 220 V. Since p.d. remains same only in parallel, therefore all the appliances and lights are joined in parallel. A switch is connected in series with each light and appliance.

In a particular section L_1, two lamps B_1 and B_2 and an appliance, say a heater, are connected in parallel to each other. The total current of all the lamps and the heater must not exceed the current carrying capacity of the fuse F_1.

18.16 Ring Main Circuit

This system is fast replacing the system described above. It consists of a ring system. This starts from the main fuse box having a fuse of 30 A (assuming that the total load will not exceed 30 A) and then goes round the rooms of the house and back to the main fuse box again.

The advantages of the system are:

1. When the fuse blows, it only affects the single appliance concerned.
2. It is easier to repair and check, as each appliance has its own fuse than to check up all the fuses of the box.
3. It is easier to add any new point anywhere.
4. At a point *A* the current will be divided into two directions, therefore even when the current of the whole system is 30A: the capacity of the cables need not be more than 15A. This saves the cost of wiring, as the insulation on a 30A cable is much more than on a 15 A cable.

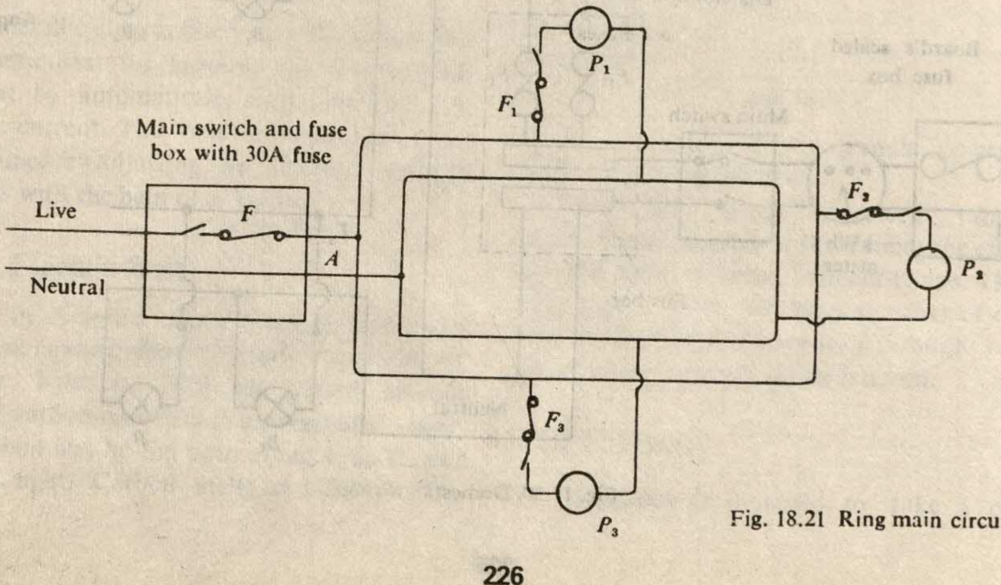


Fig. 18.21 Ring main circuit

QUESTIONS

1. What is meant by the electrical resistance of a conductor? What factors affect the electrical resistance of an object?

2. What is the relation between current, potential difference, and resistance in a circuit. How does that relation help you to define the unit of resistance?

3. State Ohm's law. What are its limitations? Describe an experiment to determine the resistance of a 2 volt torch cell. What is the difference in the resistance of the bulb when it is glowing with the normal glow than when it is not glowing?

4. Define resistivity or the specific resistance of a material. What are its units? How is it affected with the rise in temperature of the conductor?

5. Calculate the current flowing in a 2 V cell when it is connected to two resistors of 4 and 6 ohms in (i) series; (ii) parallel.

6. A circuit consists of a 2 V cell, a resistor of 2 ohms, two resistors of 4 and 8 ohms connected in parallel, and an ammeter of 1/3 ohm resistance all connected in series. Draw the circuit diagram and calculate

(i) the current in the ammeter;
(ii) p.d. across two parallel resistors;
(iii) the current through 4.0 Ω resistor;
(iv) the power expended in the 4.0 ohm resistor.

7. In the diagram shown in Fig. 18.22, if the current in 3 ohm resistor is 1.2 A. Calculate

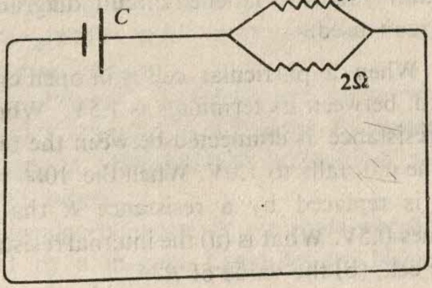


Fig. 18.22

(i) the current in the 2 ohm resistor,
(ii) the current in the cell.

8. Define volt, ampere and ohm. How are they related together. Why are ammeters connected in series and voltmeters in parallel? Why should ammeters have low resistance and voltmeters, high resistance. Explain.

9. You are given three coils each of resistance 2 ohms. Calculate the maximum and minimum values of resistances you can get by joining them.

10. Three electric bulbs marked 40 W, 60 W and 100 W are connected in parallel with a main supply of 220 V. Calculate

(i) resistance of each bulb;
(ii) current drawn by each bulb;
(iii) total resistance of the three bulbs;
(iv) total current drawn from the mains;
(v) total electrical energy in Joules converted in 5 minutes.

11. In the circuit shown in Fig. 18.23, what readings would you expect in each of the meters when

(i) S_1 is closed but S_2 and S_3 are open;
(ii) S_1 and S_2 are closed but S_3 is open and *C* records 3.0 A.
(iii) All the switches are closed, ammeter *B* reads 6 A and ammeter *C* reads 2 A.

12. A current of 2.5 A is passed through a wire of length 1 m and diameter 2 mm. If the resistivity of the material of the wire is 44×10^{-8} ohm m, calculate

(i) the resistance of the wire;
(ii) the p.d. across the wire.

13. Derive the relation between power, potential difference and the current.

Name and define the units of power and energy in electricity.

14. What is meant by the marking 100 W, 250 V on a lamp?

Find the amount of energy released when 2 A current flows through 5 ohm resistor for 10 minutes.

15. What is the resistance of a 40 W lamp operated on 220 V? How would you connect three such lamps so as to operate normally and why?

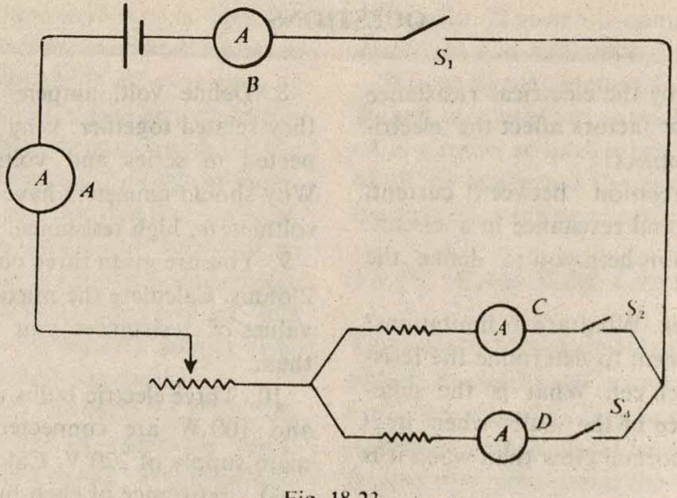


Fig. 18.23

16. What is the relation between 1 kWh and joules? Derive it.

17. State the material of which each of the following wires is made and mention the properties which make it suitable for the purposes for which they are used.
    (i) Fuse wire.
    (ii) Electric heater element.
    (iii) Filament of a lamp.
    (iv) Connecting wire.

18. Draw a clear labelled diagram of an electric bulb. Explain why
    (i) the wire used in a bulb is of coiled-coil type;
    (ii) the bulb is first evacuated and then filled with nitrogen at low pressure.

19. Draw a labelled diagram of an electric kettle. What precautions are used for safety purposes while using electric installations.

20. Four lamps of 100 W each are used daily for 5 hours and a heater marked 2 kW is used for 20 minutes a day. Calculate the cost of running these at the rate of 60 paise a unit in a month of 30 days.

21. Two bulbs have the following ratings: (i) 40 W, 220 V and (ii) 20 W, 100 V. What is the ratio of their resistances?

22. A bulb in a torch is marked 2.5 V, 0.3 A and the battery which lasts for 10 hours while using costs Rs 1.50. What is the cost of 1 kWh?

23. Draw a domestic wiring system having 3 lamps in each room. State three important precautions that you should take while wiring a house.

24. With the help of a diagram, explain the ring main system of electric wiring. What are its advantages?

25. What do you mean by electromotive force? In which ways is it different from potential difference?

26. What do you mean by internal resistance of a cell? Describe a method to find it in the laboratory. Draw a labelled circuit diagram of the circuit used.

27. When a particular cell is in open circuit the p.d. between its terminals is 1.5V. When a 10Ω resistance is connected between the terminals the p.d. falls to 1.0V. When the 10Ω resistance is replaced by a resistance R the p.d. becomes 0.5V. What is (a) the internal resistance of the cell; (b) the value of R?

19

Magnets

More than 2000 years ago man was familiar with a certain kind of iron ore which exhibited the property of magnetism.

Ancient Chinese knew that some iron ores when suspended freely come to rest pointing roughly in the north-south direction. The compass, which helps ships in oceans and scouts in the woods to find their way, was based on this principle. This stone was named 'lodestone' which means leading stone, as it was employed for leading or directing people.

19.1 Magnetic Substances

All materials show some magnetic effect, though in most cases it is so minute that special instruments are needed to detect it. Some substances are even repelled by a magnet but the repelling force is very feeble. Materials are thus classified into three kinds:

1. *Ferromagnetic* materials are those which are strongly attracted by a magnet, for example, iron, cobalt, nickle.

2. *Paramagnetic* materials are those which are weakly attracted by a magnet. Examples of paramagnetic materials are: aluminium, platinum and oxygen.

3. *Diamagnetic* materials are those which are repelled by a magnet. Examples are: bismuth, copper and gold.

19.2 Poles of a Magnet

Activity 1. Put fine iron filings on a piece of paper. Roll a bar magnet in the iron and then lift it up. Repeat with a U-shaped magnet.

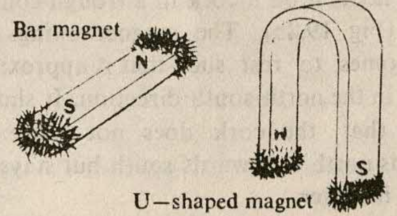


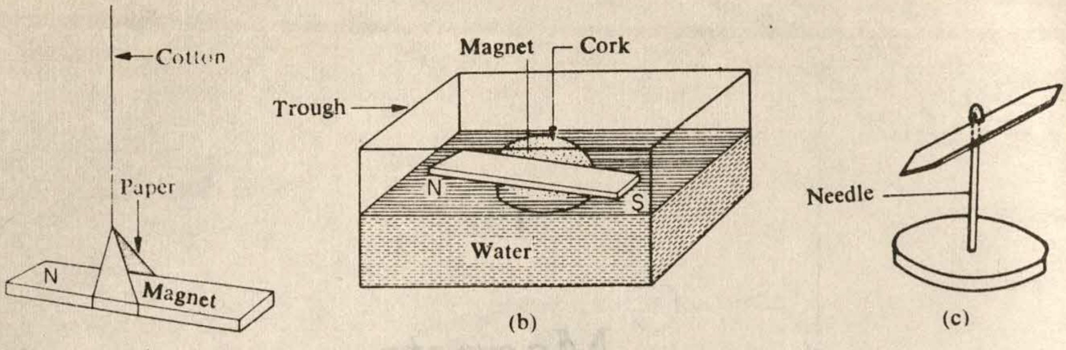
Fig. 19.1

It is found that maximum amount of iron filings cling to the magnet at the ends. The force of attraction decreases towards the middle and there is almost none at the centre.

The regions of strongest magnetism near the ends are called the **poles** *of the magnet, or the* **magnetic poles**. Most magnets have two poles. A magnetic pole is not a *pin-point* but is a *region* and the poles always exist in pairs. One pole cannot be isolated from another.

19.3 North and South Poles

Activity 2. Suspend a bar magnet freely with no magnetic material near it (Fig. 19.2a). You will notice that it always comes to rest in the same direction which is *roughly* geographic north-south. The end which points towards north is called *north-seeking pole* of the magnet or more simply the *north pole* (N-pole). The other end which points towards south is called



(a) (b) (c)

Fig. 19.2

the *south pole*. In commercially available magnets, the north pole is sometimes coloured red and the south pole grey.

Another method to suspend a magnet freely is to float it on a cork in a trough containing water (Fig. 19.2b). The magnet swings round and comes to rest such that it approximately points in the north-south direction. It should be noted that the cork does not move either towards north or towards south but stays where it was in water.

The third way is to pivot a light magnetic needle on a sharp pivot. On spinning, it always comes to rest in approximately the north-south direction. This is called *compass needle* and is shown in Fig. 19.2c.

19.4 Laws of Magnetism

Activity 3. Suspend a magnet freely and slowly bring another magnet near it such that either N-poles or S-poles of the two magnets face each other (Fig. 19.3). Now reverse one of the magnets so that the N-pole of one faces the S-pole of the other as shown in Fig. 19.4.

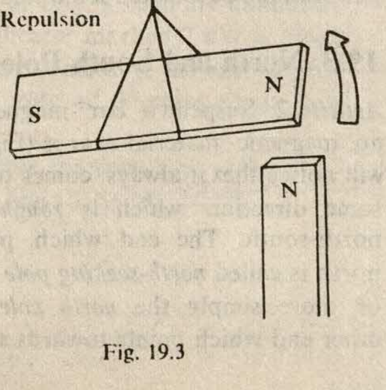


Fig. 19.3

It is noticed that a north pole repels a north pole but attracts a south pole. Similarly a south pole repels a south pole but attracts a north pole. To summarise:

Unlike poles attract and like poles repel one another.

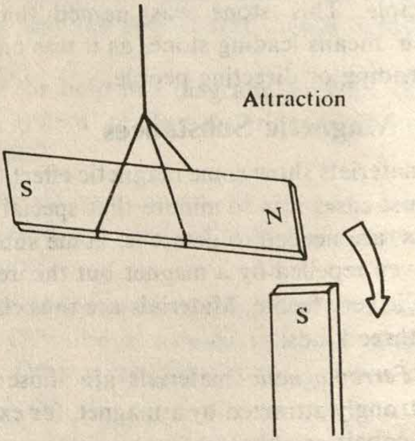


Fig. 19.4

19.5 Test for Magnetism

If a metal bar is attracted by a magnet, it is difficult to tell whether the bar is a permanent magnet as attraction occurs not only between unlike poles but also between a magnet and an unmagnetised piece of iron. The only true test is to see whether it can be repelled by the other end of the magnet.

Repulsion, and not attraction, is the sure test for magnetism.

19.6 Magnetic Induction

If the north pole of a magnet is brought near an unmagnetised piece of iron, the latter becomes magnetised with south pole on the nearer end and a north pole at the farther end (Fig. 19.5).

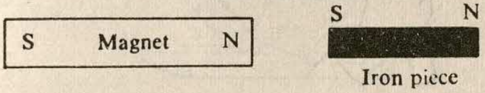


Fig. 19.5

This process is called **magnetic induction**.

Magnetic induction *is a process by which a piece of a magnetic material becomes a magnet when it is placed near or touching a permanent magnet.*

The iron piece is attracted by the magnet because opposite poles are nearer each other than the similar poles. Thus induction always preceds attraction. An induced magnet can also induce poles in another piece of iron or a magnetic substance. In this way a magnet can pick up two or three pieces of iron (Fig. 19.6).

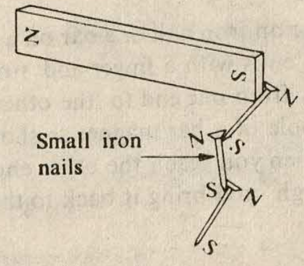


Fig. 19.6 Magnetisation by induction

19.7 Magnetic Induction in Iron and Steel

Activity 4. Keep iron and steel bars of the same size over iron filings and touch the upper end of the two bars with one pole of a magnet. Iron and steel bars get magnetised and attract iron filings towards them (Fig. 19.7a). Iron bar attracts more filings than steel. Remove the magnet and note what happens.

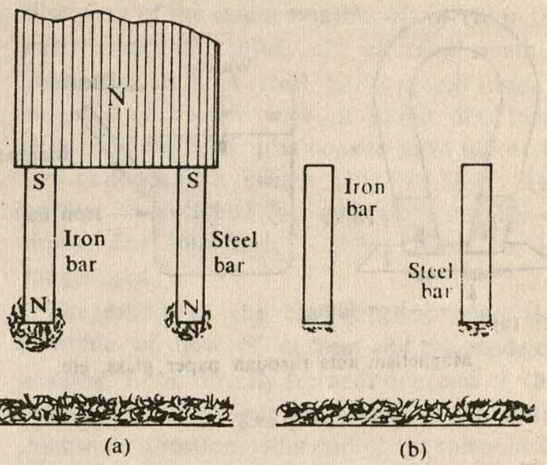


Fig 19.7

On removing the magnet, the iron piece drops almost all the iron filings clinging to it while the majority of filings keep sticking to the steel bar. We may summarise that steel gets magnetised less than the iron under similar conditions but retains most of its magnetism when the magnetising source is removed. We say that:

Iron is more susceptible than steel but is less retentive.

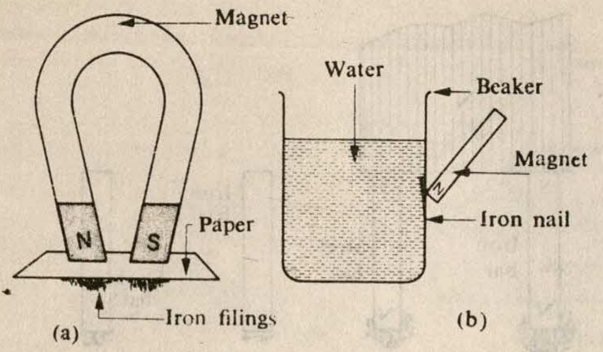
This is why iron is used in temporary magnets such as electromagnets, and steel is used in making permanent magnets.

19.8 Magnetic Screening

Activity 5. Place iron filings on a table and cover them with a paper or a light cardboard. Move the two poles of a horse-shoe magnet on the cardboard and then lift it up. It is observed that the cardboard lifts up along with iron filings as shown in Fig. 19.8a.

Place an iron nail in a beaker containing water. Hold a magnet with one pole touching the side of the beaker near the bottom. Move the magnet up along the side of the beaker. It is noticed that the nail is attracted by the magnet and moves up along with the pole of the magnet (Fig. 19.8b).

Place a small compass needle in the middle of an iron ring. Move a magnet outside the ring.

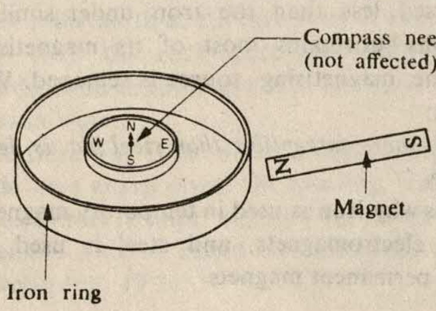


Magnetism acts through paper, glass, etc.

Fig. 19.8

The needle is not affected by the magnet and keeps on pointing in the same direction as shown in Fig. 19.9.

The experiment shows that magnetic influence acts through non-magnetic substances like paper and glass, etc. but not through magnetic substances like iron or steel. They screen off the effect of a magnet.



Magnetism does not act through iron

Fig. 19.9

We can stop the action of a magnet on a substance by surrounding it with a ring or hollow sphere or cylinder of iron or any other magnetic substance. *This phenomenon is called magnetic screening.* Antimagnetic watches have a steel ring around its moving parts.

19.9 Making Magnets (Magnetisation)

About 400 years ago, magnets were made by heating an iron bar until it was red and then hammering it while holding it in north-south direction as it cools (Fig. 19.10). The iron bar gets magnetised through induction by the Earth's magnetism.

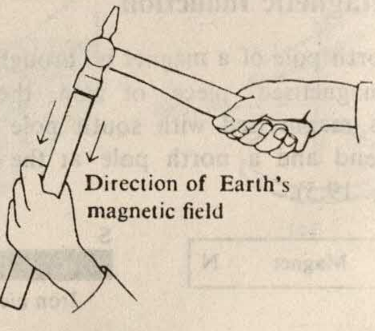

Direction of Earth's magnetic field

Fig. 19.10

Numetal is an alloy of nickle, iron, copper and chromium which gets magnetised by induction by simply holding it in north-south direction. The end which points north becomes a north pole as the Earth's magnetic north pole is in the geographic south. It loses magnetism when placed in east-west direction. Bases of ships, steel pipes of water and gas get slightly magnetised by the Earth's magnetism.

An iron bar can be magnetised by stroking it with a magnet in the following ways:

1. *Single Touch*

Activity 6. Place an iron nail or a bar on a table. Hold one of its ends with a finger and stroke it about 20 times from one end to the other with say the north pole of a bar magnet as shown in Fig. 19.11a. When you reach the other end, lift the magnet high and bring it back to the first end.

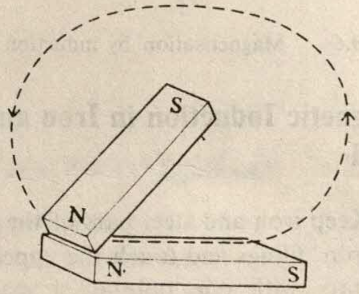


Fig. 19.11 (a) Single touch method

Using a compass needle it is found that the *end from where stroking is started becomes a* *similar pole and the other end becomes the opposite pole to that of the stroking pole.*

2. *Double Touch*

Place north and south poles of two magnets in the middle of an iron piece and stroke the piece with them a number of times as shown in

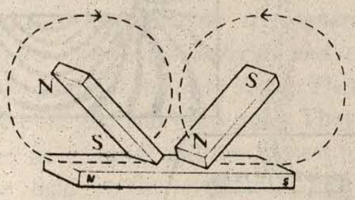


Fig. 19.11 (b) Double touch method

Fig. 19.11b. This method is suitable when there is something in the middle of the piece which obstructs single stroke as is the case in a compass needle.

If the stroking is done with two similar poles, say N-poles, as shown in Fig. 19.12, we get a magnet with south poles at the ends and north

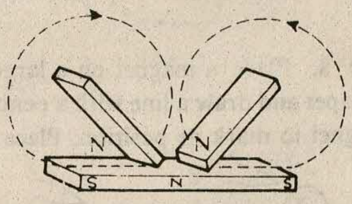


Fig. 19.12

pole in the middle. Such a magnet is called a magnet with *consequent poles*. It loses its magnetism soon.

3. *Electrical Method*

Single touch and double touch methods of magnetisation were used in tne past. After the discovery of the magnetic effect of current in the early nineteenth century, the electrical method is mostly used. A steel bar is placed inside a solenoid of copper wire of about 500 turns (Fig. 19.13a) and it is connected to a 6 or 12 volt battery and a switch (Fig. 19.13 b) The current is switched 'on' and 'off' a number of times. The steel rod is then found to be magnetised.

The polarity of the bar depends upon the direction of flow of current and the mode of winding. Look directly towards one end of the solenoid; if the current is flowing in an anti-clockwise direction, that end of the solenoid is an N-pole and the end of the steel rod near to this becomes an N-pole. The other end, where the direction of current flow is clockwise becomes an S-pole.

Current is only passed for a short duration at a time. If it is passed for a long time it causes overheating which may damage the coil.

19.10 Demagnetisation

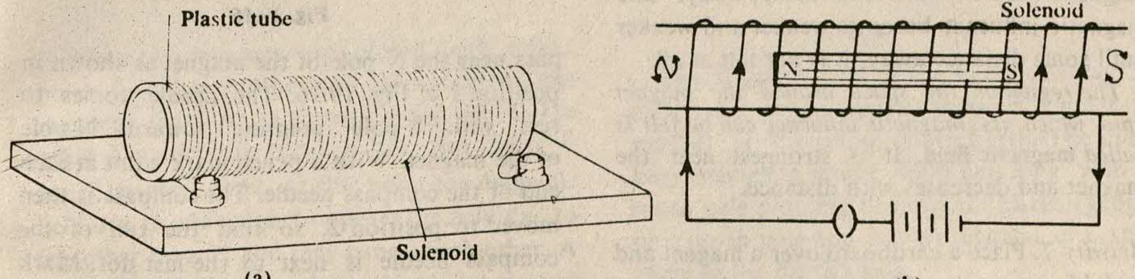
This is a process in which a magnet loses its magnetism. It can be done in three ways:

1. *Rough Handling*

The magnetism of a magnet becomes weaker and finally disappears on rough handling by either dropping it violently on the floor many times or hammering it while it is placed along the east-west direction.

2. *Electrical Method*

The best way to demagnetise a magnet is by placing it in a solenoid through which an alternating current is made to flow by connecting it



(a)

(b)

Fig. 19.13

to a 12-24 volts main transformer. The solenoid should be placed in east-west direction and the magnet is then withdrawn to a great distance from the solenoid (Fig. 19.14).

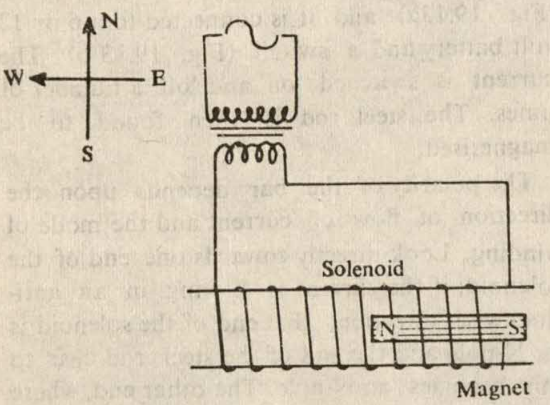


Fig. 19.14

The alternating current reverses the poles of the magnet 50 times a second; they become weaker and weaker till no strength is left.

3. *Heating*

Heat the magnet red hot and then allow it to cool while it is placed in east-west direction. The magnet loses almost all its magnetism. Nickle loses magnetism at 360°C, iron at 750°C and cobalt at 1100°C. This is not recommended as a practical method, since heat treatment spoils steel.

19.11 Magnetic Fields

Bring a compass needle near a magnet, it gets deflected. Move the compass needle above, below and to the side of the magnet, it gets deflected showing thereby that magnetic influence extends all round the magnet. Take the magnetic needle further and further away. The magnetic influence becomes weaker and weaker until some distance away, it is not felt at all.

The region or the space around the magnet upto which its magnetic influence can be felt is called **magnetic field.** It is strongest near the magnet and decreases with distance.

Activity 7. Place a cardboard over a magnet and sprinkle some iron filings on it evenly and not too thickly. Tap the side of the card with a pencil and note the pattern formed.

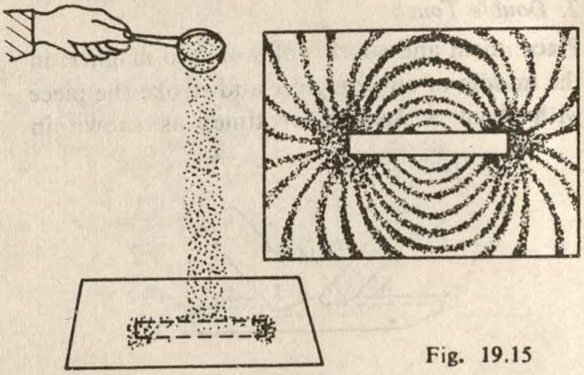


Fig. 19.15

The iron filings arrange themselves along lines called *magnetic lines of force* or *field lines.* The pattern is densest near the poles where the field is the most intense. There is no strip of space sandwiched between two strong fields where the field is zero.

If the magnetic field is weak, its mapping is done with a much more sensitive small compass needle.

Activity 8. Place a magnet on a large sheet of white paper and draw a line with a pencil around the magnet to mark its position. Place the compass near the N-pole of the magnet as shown in position 1 of Fig. 19.16. The needle comes to rest with S-pole pointing towards N-pole of the magnet. With a pencil mark a dot at each end of the compass needle. The compass is then moved to position 2, so that the tail of the compass needle is next to the last dot. Mark another dot against the N-pole of the needle.

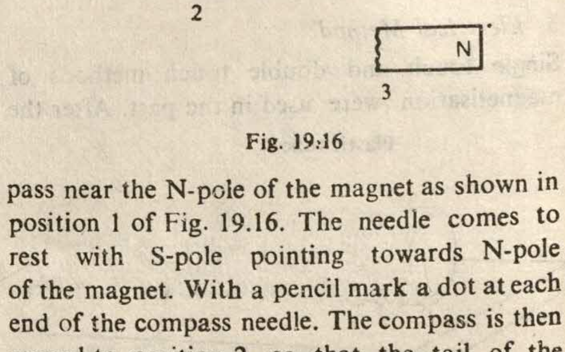


Fig. 19.16

The compass is moved to position 3, and a dot is marked again against the N-pole of the needle and so on. Repeat this process until the line traced out either returns to the magnet or goes out of the paper. The whole process may then be repeated starting off from a different point near the N-pole.

A **line of force** *is a line in a magnetic field along which a N-pole moves freely and its direction is from magnetic north to south.* These lines start on N-pole and end on S-pole. They never touch, they never cross and are closest together where the field is the strongest. Fig. 19.17a shows the magnetic field around a bar magnet and Fig. 19.17b shows the field around a horseshoe magnet.

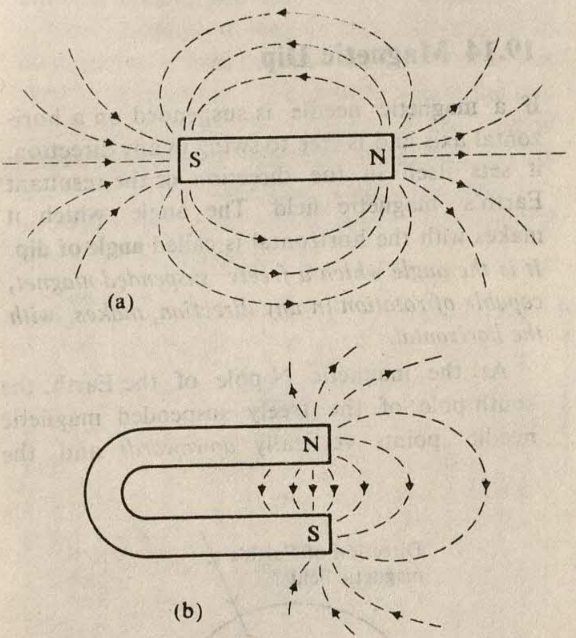


Fig. 19.17

When two magnets are placed with unlike poles facing each other and close together, the magnetic field is as shown in Fig. 19.18. The point *X* marked in between the two poles is called **neutral point**. At this point the magnetic field due to one magnet opposes the field due to the other magnet and they cancel each other. A compass needle placed at this point is not affected by the two magnets and stands in any direction.

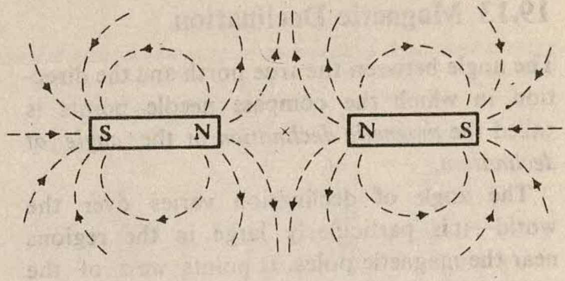


Fig. 19.18

19.12 The Earth's Magnetism

Have you ever wondered why a magnetic needle always points approximately in the north-south direction? It is because the Earth itself behaves as a huge magnet with its magnetic poles near the geographic N and S poles. The north magnetic pole lies to the west of north geographic pole at a distance of about 2000 km from it on an island off the north coast of Canada, and the south magnetic pole is located east of the south geographic pole in the sea off the coast of Antarctic continent (Fig. 19.19).

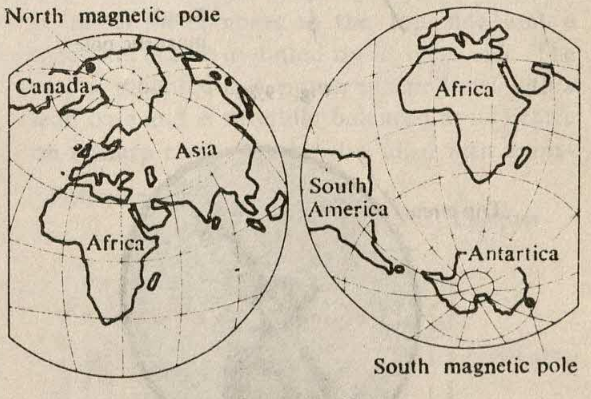


Fig. 19.19

The magnetic field of the Earth can be described by imagining that there is a giant bar magnet at the centre of the Earth. The imaginary magnet is about 4000 km long with its south pole pointing towards the Earth's geographic north pole and its axis inclined at a small angle to the Earth's axis.

19.13 Magnetic Declination

The angle between the true north and the direction in which the compass needle points is called the *magnetic declination* or the *angle of declination.*

The angle of declination varies over the world—it is particularly large in the regions near the magnetic poles. It points west of the true north in the northern hemisphere of the Earth and points east of the true south in the southern hemisphere. There are places on the Earth where the angle of declination also varies at the same place from year to year.

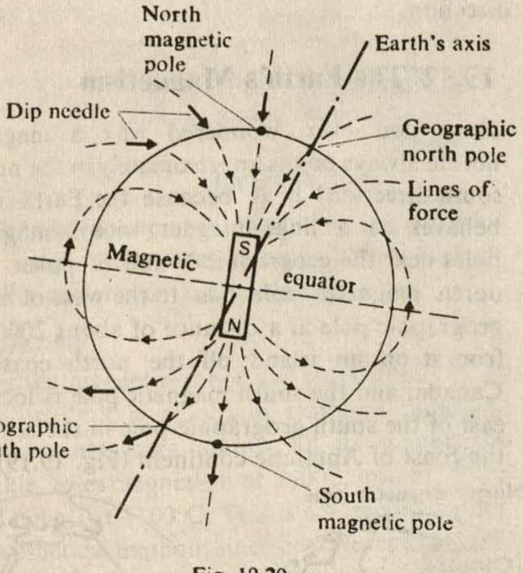


Fig. 19.20

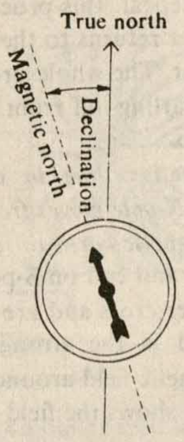


Fig. 19.21

19.14 Magnetic Dip

If a magnetic needle is suspended on a horizontal axis and is free to swing in any direction, it sets itself in the direction of the resultant Earth's magnetic field. The angle which it makes with the horizontal is called **angle of dip.** *It is the angle which a freely suspended magnet, capable of rotation in any direction, makes with the horizontal.*

At the magnetic N-pole of the Earth, the south pole of the freely suspended magnetic needle points vertically *downwards* and the

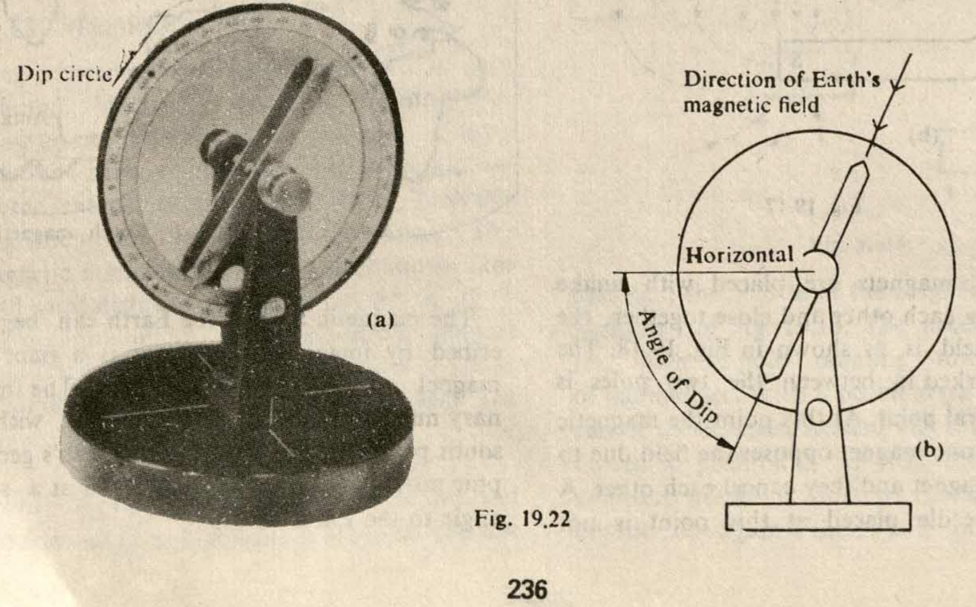


Fig. 19.22

angle of dip is 90°. Similarly at the magnetic south pole of the Earth, the north pole points vertically downwards and angle of dip there is also 90°. At places half-way in between the two magnetic poles of the Earth, the needle points horizontally and angle of dip is 0°. The horizontal plane passing through all such places on the Earth having angle of dip equal to 0° is called the *magnetic equator*.

19.15 Neutral Points

You have already studied that a neutral point is the point at which the magnetic field due to one magnet is equal and opposite to the field of another magnet and they cancel each other.

Now, around a magnet there is not only its own magnetic field but also the field due to the earth's magnetism. The points where the two cancel each other are known as the **neutral points**. A magnetic needle placed at these points can point in any direction. Two cases arise.

(a) *When north pole points north:* The neutral points are as shown in Fig. 19.23.

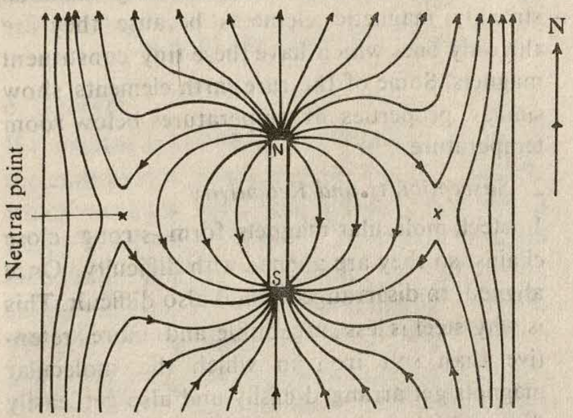


Fig. 19.23 Field around a magnet with N-Pole pointing north.

(b) *When north pole points south:* The neutral points are as shown in Fig. 19.24.

19.16 Mariner's Compass

The magnetic needle of the pocket compass easily swings around and it is difficult to take readings unless the compass is perfectly still. Such a compass cannot be used on a ship in rough seas. This difficulty is overcome in a specially designed mariner's compass. It consists of a circular card marked with the 32 points of the compass on the top side and a magnetic needle mounted on its inner side. The card is mounted in a non-magnetic bowl with a lead base and is carefully balanced at its centre on a sharp pivot. The bowl is filled with a mixture of water and alcohol which resists the card from swinging about too much and also buoys up the card so that it does not rest too heavily

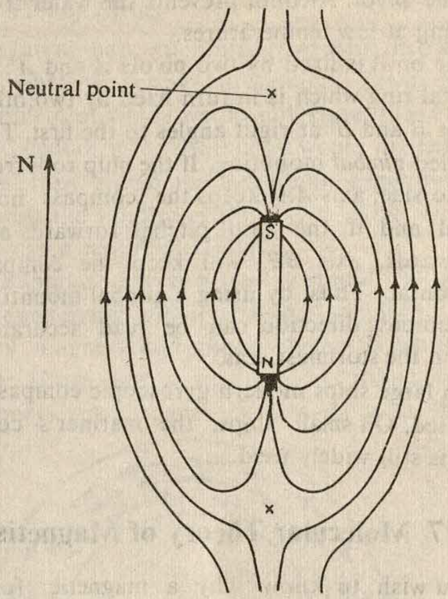


Fig. 19.24 Field around a magnet with N-Pole pointing north.

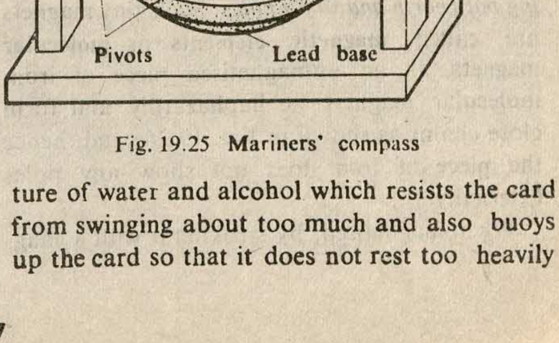


Fig. 19.25 Mariners' compass

on the pivot. Alcohol prevents the water from freezing at low temperatures.

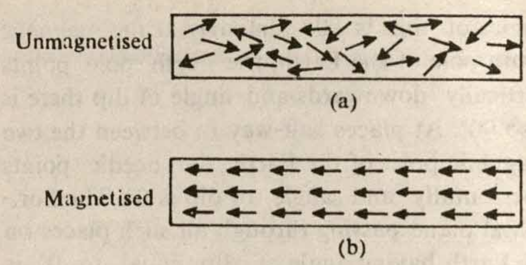
The bowl is fixed by two pivots A and A' to a metal ring which is in turn fixed by two other pivots B and B' at right angles to the first. This is called *gimbal* mounting. If the ship rolls from side to side, axis AA' keeps the compass horizontal and if the ship pitches forwards and backwards, axis BB' will keep the compass horizontal. Thus, by using a gimbal mounting, the compass direction can be read accurately even in the stormiest seas.

On large ships modern gyroscopic compasses are used. On small ships, the mariner's compass is still widely used.

19.17 Molecular Theory of Magnetism

If you wish to know why a magnetic force behaves in a particular way we can answer it by formulating an appropriate theory, but we cannot answer why a magnetic force exists. Magnetic forces exist just in the same way as gravitational and electrical forces exist. Some questions which you may ask about the behaviour of a magnetic force are: Why are some materials more magnetic than others? Why does a bar magnet lose magnetism on heating and why does an iron piece get magnetised by stroking it with a magnet? Why does a magnet attract an unmagnetised piece of iron? Why does a bar magnet, when broken in the middle, seem to have new poles at the two new ends? These and many other questions can be answered by the simple **molecular theory of magnetism.** It states that *ferromagnetic materials, whether in a magnetised or unmagnetised condition, are made up of a very large number of particles which are themselves tiny magnets having both north and south poles.* Such tiny magnets are called **magnetic elements** or **molecular magnets**. In an unmagnetised piece of iron, molecular magnets lie haphazardly and form close chains as shown in Fig. 19.26a and hence the piece of iron does not show any poles externally.

When magnetised, by stroking it with a magnet or by placing it in a magnetic field, molecular magnets tend to arrange themselves with north poles pointing one way and the south poles the other way as shown in Fig. 19.26b.



(a)

(b)

Fig. 19.26

Lined up this way, except at the ends, north and south poles of molecular magnets cancel each other's affect on external objects. At one end there are free or unpaired north poles and at the other end an equal number of south poles; thus the piece behaves as a magnet.

A number of facts about magnetism can easily be explained with the help of the above theory:

1. *Magnetic Substances*

Iron, cobalt and nickle are the only common strongly magnetic elements because they are the only ones which have these tiny constituent magnets. Some of the rare earth elements show similar properties at temperatures below room temperature.

2. *Susceptibility and Retentivity*

In steel, molecular magnets form strong close chains, so they are aligned with difficulty. Once aligned, to disarrange them is also difficult. This is why steel is less susceptible and more retentive than soft iron in which the molecular magnets get arranged easily and also get easily disarranged.

3. *Saturation Stage*

On stroking a piece of iron with a magnet, progressively more and more molecular magnets get arranged and magnetism of the piece increases. A stage is reached when all molecular magnets get arranged. Then any further rubbing does not increase magnetism; such a stage is called *saturation stage*.

4. *Heating and Rough Handling*

Heating or rough handling produces rapid motion of the molecules and destroys magnetism by breaking up the alignment of molecular magnets. Cooling is likely to restore magnetism if it is placed in north-south direction due to the induction of the Earth's magnetism. When placed in east-west direction it loses magnetism on cooling.

5. *Breaking a Magnet*

On breaking a magnet two complete magnets are produced because it separates sets of paired N-S ends of tiny magnets. Thus, at each end where it is broken opposite poles becomes free and hence each broken part behaves as a magnet (Fig. 19.27).

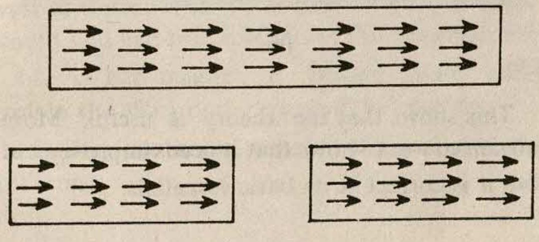


Fig. 19.27 **Breaking of a magnet**

6. *Keepers*

If a magnet is stored singly, then free poles at the ends induce opposite poles on tiny magnets which weakens their magnetism. To avoid it magnets are stored in pairs, with unlike poles alongside each other. Pieces of soft iron, called *keepers*, are placed across both ends. The pieces get magnetised by induction in such a way that tiny magnets form continuous chains, with the result that no poles are left free and the magnets are not likely to lose magnetism.

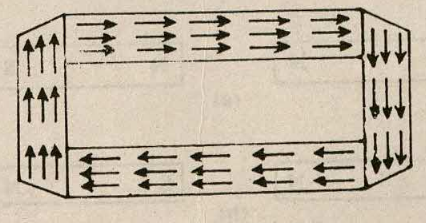


Fig. 19.28 Keepers

7. *Test of Theory*

So far we have attempted to explain theoretically what we knew beforehand. Let us pose a problem of which we do not know the answer and deduce what the theory would predict. We can then check the prediction experimentally to test the validity of the theory. This is what we call a *scientific method.*

Suppose we have a steel ring and we rub its circumference with a pole of a magnet to align tiny magnets and check whether it can attract iron filings like a magnet. According to the theory, tiny magnets will arrange themselves end to end in a continuous chain as shown in Fig. 19.29a. There will be no free poles, and the ring will not act as a magnet. It is found experimentally that it does not attract iron filings as shown in Fig. 19.30a.

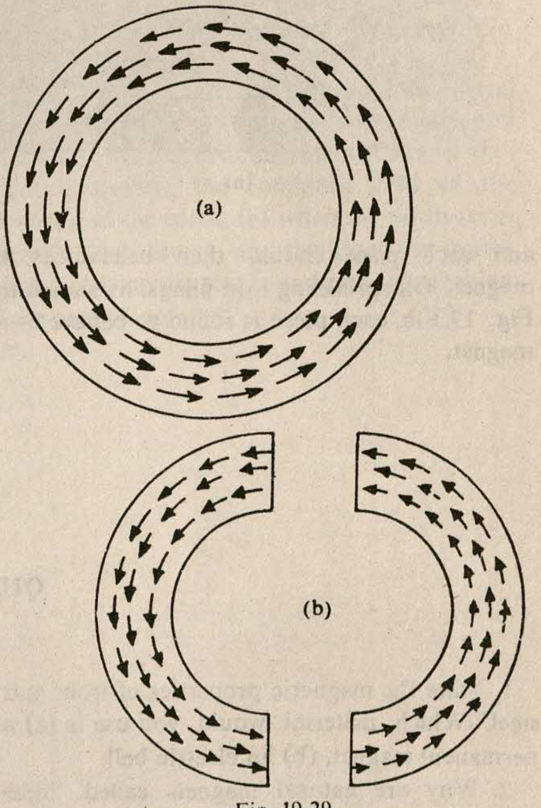
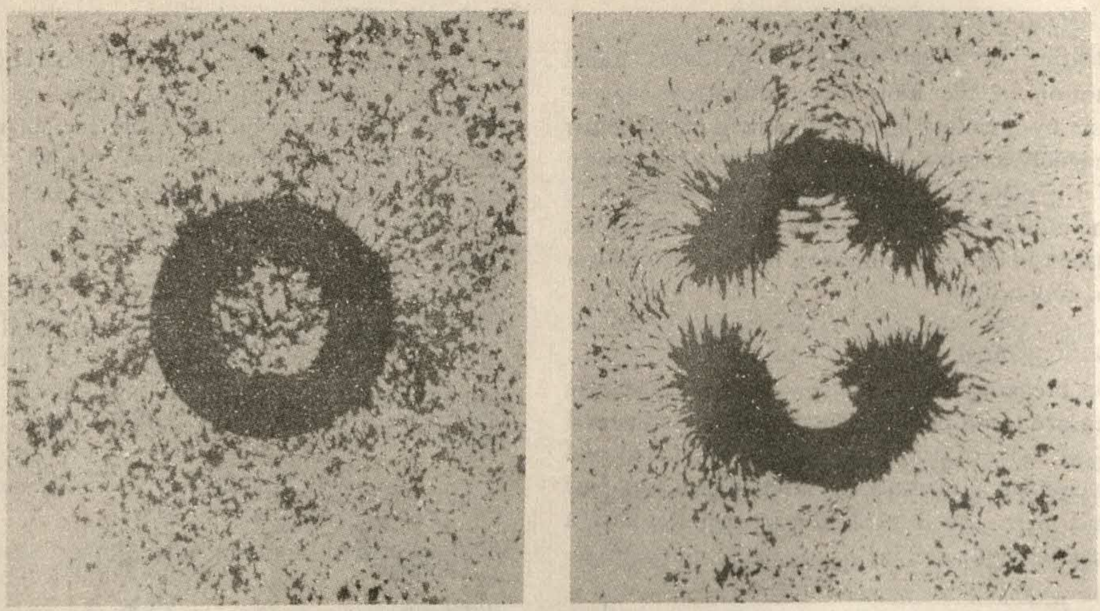


Fig. 19.29

Break the ring into two halves. When this is done, according to the theory, poles of tiny magnets will become free at the ends (Fig. 19.29b)



(a)

(b)

Fig. 19.30

and each piece should then behave as a magnet. On sprinkling iron filings, as shown in Fig. 19.30b, each piece is found to behave as a magnet.

This shows that the theory is useful. More advanced work shows that it needs improvement but it is correct in its basic essentials.

QUESTIONS

1. State the magnetic properties of iron and steel. Which material would you use in (a) a permanent magnet, (b) an electric bell.

2. Why are natural magnets called 'lodestones'?

3. What is meant by the term magnetic pole? How would you check that a particular end of a magnet is a N-pole?

4. Explain what is meant by the term magnetic induction. Why is a piece of iron placed near a magnet attracted towards it? Explain.

5. Explain why two steel needles hanging from an S-pole of a magnet do not remain parallel.

6. What is meant by the terms (a) magnetic field, (b) line of force? Draw the magnetic field of a bar magnet.

7. Draw the magnetic fields due to two bar magnets arranged in Fig. 19.31a, b.

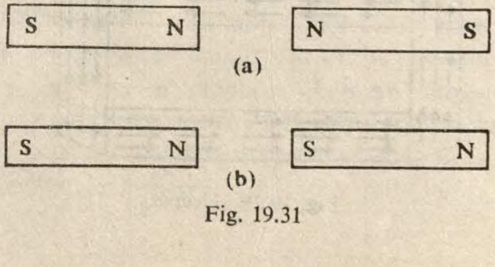


Fig. 19.31

8. How would you screen off a region near a magnet from the effect of the field? Illustrate your answer with a diagram.

9. How would you magnetise a steel rod by (a) permanent magnet, (b) electrical current, so that a particular end of the rod becomes a north pole? Illustrate your answer with labelled diagrams.

10. Draw a diagram to show the Earth's magnetic field. Mark on the diagram the places where the angle of dip is 0° and 90°.

11. What is meant by the angle of declination and the angle of dip?

12. How does a Mariner's compass differ from an ordinary one? Describe its construction and give a neat diagram to illustrate your answer.

13. The angle of declination at a place is 7° west of north. What do you mean by it? How would you find *true north* from this information?

14. A bar magnet is heated. State and explain the effect on its magnetic properties.

15. Why do some watches have a case of soft iron?

16. Describe how a magnet can be demagnetised by an alternating current and an iron bar can be magnetised by a direct current. Draw neat diagrams in support of your answer.

17. Explain why the hulls of most iron ships are permanently magnetised. How is the effect of the steel of a ship on the ship's compass neutralised.

18. What are the essential features of the molecular theory of magnetism? How can the theory be used to explain (a) a specimen of iron cannot be magnetised beyond saturation stage; (b) soft iron pieces are used in storing magnets; (c) on breaking a magnet into two halves each half behaves as a magnet (d) iron is a magnetic material.

19. Explain the meaning of the term neutral point. A bar magnet is placed horizontally, and parallel to the magnetic meridian. Draw a diagram illustrating the combined field of the magnet and the earth, (a) when the north-seeking pole points north, and (b) when the north-seeking pole points south. Indicate the position of the neutral points.

20

Electromagnetism

In 1819, a Danish science teacher Hans Orsted observed that when a wire was arranged above and parallel to a compass needle and current was passed through it as shown in Fig. 20.1a, the N-pole of the needle was deflected towards west to a position that was no longer parallel to the wire. On reversing the direction of current, the N-pole was deflected towards east (Fig. 20.1b).

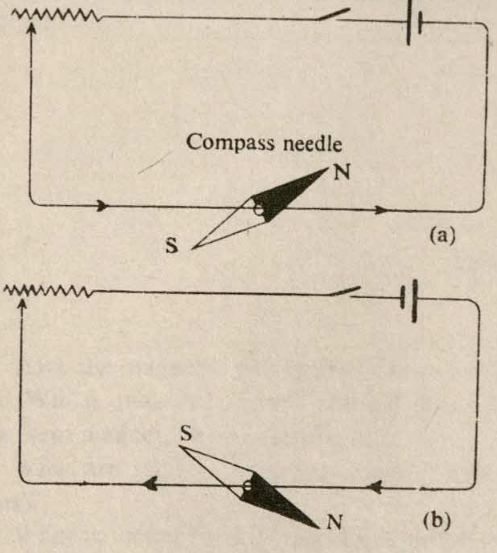


Fig. 20.1

A magnetic needle can be deflected only by another magnetic field. The current in the wire, therefore, must be producing a magnetic field. *Magnetism produced by current is called* **electromagnetism**.

Soon scientists started investigating this classroom discovery which was a major breakthrough in the development of the concepts of electromagnetism. In 1823, the first iron core electromagnet was made. Faraday produced continuous rotation of a wire by passing current through it when it was suspended freely in a magnetic field. This laid the foundation of electric motors and all electrical gadgets such as fans, mixies, refrigerators, air-conditioners, etc. which utilise the electric motor. In 1930, Joseph Henry and in 1931 Faraday realised that current could be produced in a conductor placed in a changing electric field. Thus was laid the foundation of the dynamo which has made possible the widespread use of electricity today.

20.1 Field Round a Straight Wire

Activity 1. Set up vertically a large rectangular coil of about 10 turns of thick insulated copper wire and pass one of its sides through a hole in a piece of cardboard. Connect it in series with a rheostat, a switch, an ammeter and a battery of 2-3 accumulators as shown in the Fig. 20.2.

Put in the key and adjust the rheostat so that a current of 2-3 amperes passes through the coil. Map the field around the wire either using iron filings or a compass needle. It is found that the lines of force are concentric circles with the wire as centre.

The direction of the lines of force can be

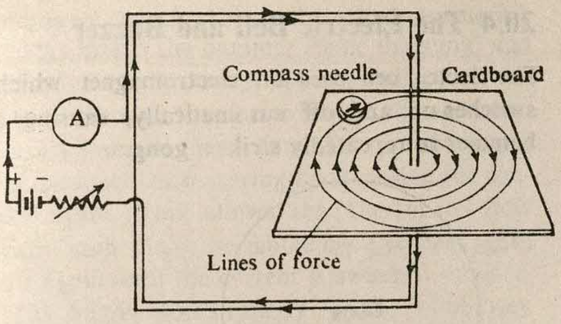


Fig. 20.2

worked out by Maxwell's *right hand grip rule*. Imagine the wire gripped in the right hand with the thumb pointing along the wire in the direction of the current. Then the direction of the fingers will give the direction of lines of force (Fig. 20.3).

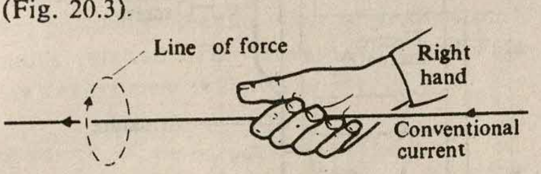


Fig. 20.3 **Right hand grip rule**

On reversing the direction of current by interchanging the connections of the battery, the N-pole of the compass needle is found to point in the opposite direction, i.e. the direction of field is reversed.

20.2 Field Due to a Circular Coil

Activity 2. Bore two holes in a sheet of cardboard and pass insulated wire in the cardboard so as to get a circular coil of about 10 turns as shown in the Fig. 20.4. Sprinkle iron filings on the cardboard round the wire passing through the holes and pass a current of about 3A. Gently tap the cardboard. The iron filings arrange themselves in concentric circles round the wire as centre.

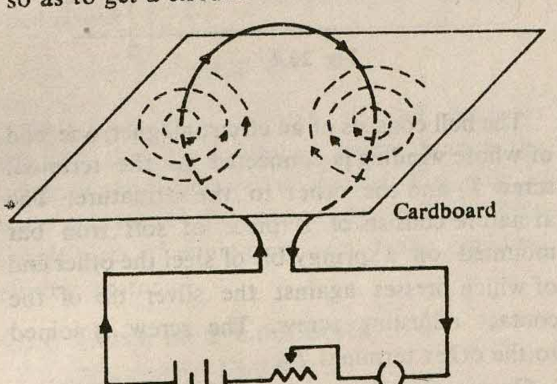


Fig. 20.4

The lines of force are nearly parallel to one another on a small space in the middle of the coil, showing thereby that the field is uniform over a small region around the centre of th coil. One face of the coil behaves as an N-pol and the other as an S-pole.

20.3 Field Due to a Solenoid or Long Coil

A long cylindrical coil of wire is called a solenoid and its magnetic field is made up of the fields of narrow circular coils in series. They add together to make a strong field like that of a bar magnet. One end *P* of the solenoid acts as a south pole and the other end *Q* as a north pole.

Which end acts as a north pole and which as the south can be worked by looking directly at

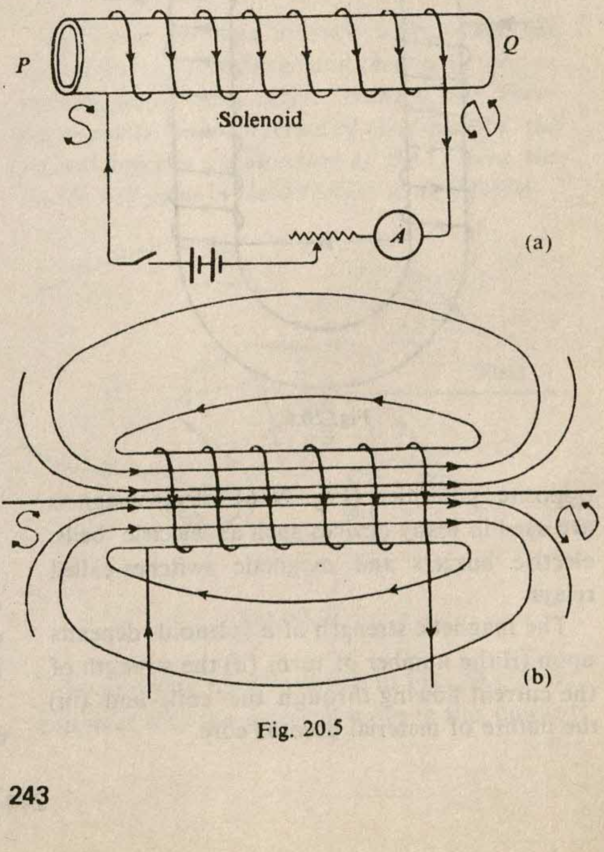


Fig. 20.5

the ends. If the current is going round in a clockwise direction that end is a south pole as shown in Fig. 20.5b. If the current is flowing in an anticlockwise direction, that end is a north pole.

Any magnetised substance placed inside the coil gets magnetised. A strong electromagnet can be easily made by winding large number of turns of insulated copper wire round a piece of soft iron. Soft iron behaves as a temporary strong magnet when current is passed through the coil. The substance round which the coil is wound is called a *core* and a solenoid with a core is called an *electromagnet*. When the current is switched off the iron loses its magnetism.

In a horse-shoe electromagnet, there are two solenoids wound in opposite directions on two soft iron pieces, which are joined by another soft iron piece. As the wire is wound round in opposite directions, the two free ends have opposite polarities (Fig. 20.6). Electromagnets are used in many devices such as electric bells, electric buzzers and magnetic switches called relays.

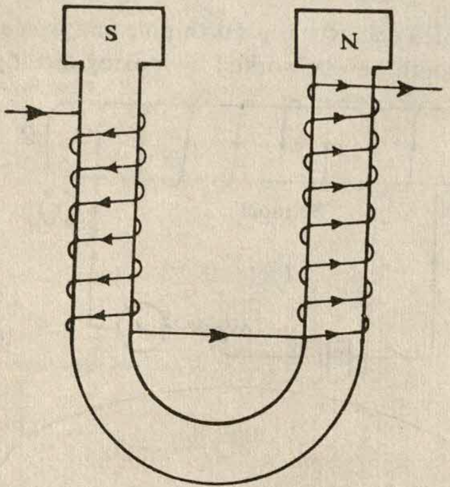


Fig. 20.6

The magnetic strength of a solenoid depends upon (i) the number of turns (ii) the strength of the current flowing through the coil, and (iii) the nature of material used as core.

20.4 The Electric Bell and Buzzer

The electric bell uses an electromagnet which switches on and off automatically, causing a hammer to repeatedly strike a gong.

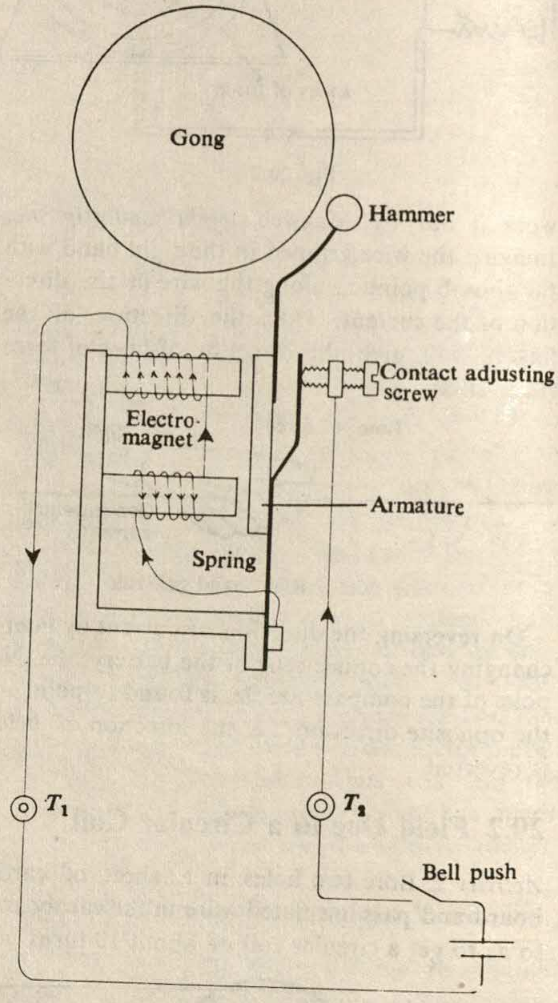


Fig. 20.7

The bell consists of an electromagnet, one end of whose winding is connected to the terminal screw T_1 and the other to the armature. The armature consists of a piece of soft iron bar mounted on a springy bit of steel the other end of which presses against the silver tip of the contact adjusting screw. The screw is joined to the other terminal T_2.

On pressing the push button the circuit is completed and current flows through the electromagnet which attracts the armature towards it. This makes the hammer strike the gong and separates the contacts. This switches off the current through the electromagnet which consequently loses its magnetism. The armature and the hammer now spring back closing the contacts again. This allows the current to flow again such that the whole cycle repeats again and again until the current is switched off.

The buzzer works exactly in the same way except that there is no gong. The sound is produced by the vibration of the armature itself.

20.5 Faraday's Rotation Experiment

After Orsted's discovery of the magnetic effect of an electric current, Faraday realised that it was possible to use this effect to produce continuous rotation. The modern version of Faraday's experiment is shown in Fig. 20.8.

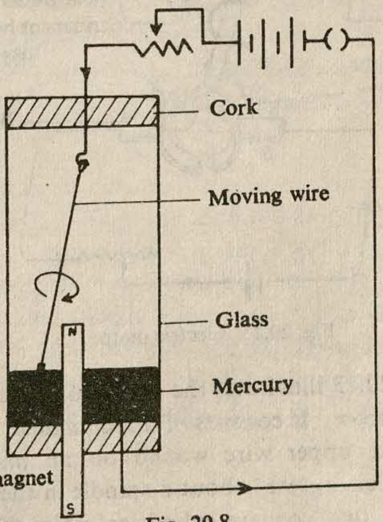


Fig. 20.8

Switching on a current of 2-3 amperes through the wire, contact is made through the mercury and the circuit completes. The wire is observed to revolve round the magnet. This simple piece of equipment was really the first electric motor.

20.6 Force on a Conductor in a Magnetic Field

Activity 3. Place a light aluminium strip across a strong magnetic field between the two poles of a powerful horse-shoe magnet and pass a current of several amperes in one direction, and then in the opposite direction in the strip. It is observed that the strip first moves in one direction and then in the reverse direction.

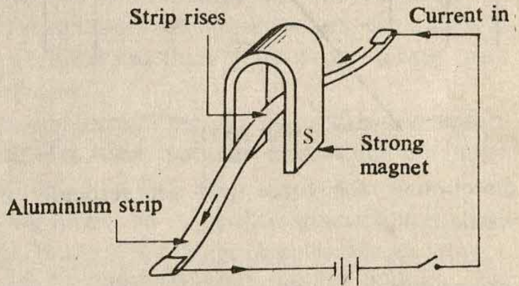


Fig. 20.9

It is noticed that the direction of motion of the strip or the force acting on the strip is at right angles to both, the direction of the field and the current. Prof. J.A. Fleming gave a rule relating the direction of motion of the strip to the direction of the current and the field. According to Fleming's left-hand rule:

Hold your left hand in such a way that the second-finger, fore-finger and the thumb are at right angles to each other. Then, if the Fore-finger points in the direction of the Field and the seCond-finger in the direction of the Current, the thuMb will point in the direction of the Motion.

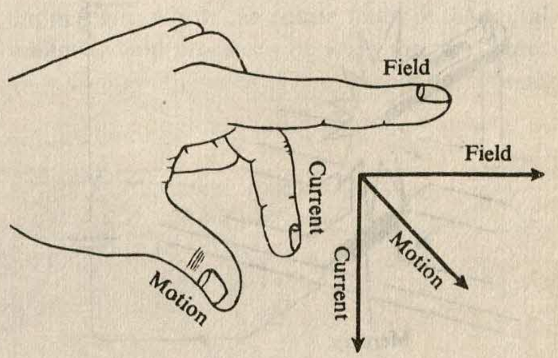


Fig. 20.10

By applying the above rule in Fig. 20.11, you can infer that the wire will move in the upward

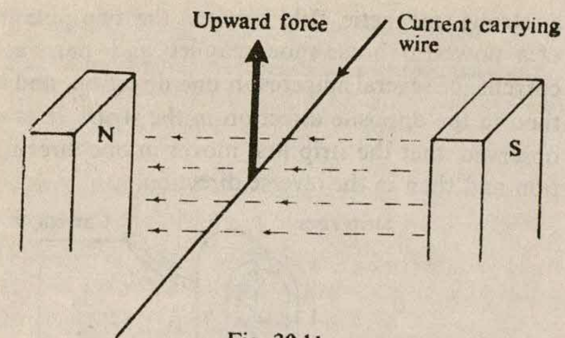


Fig. 20.11

direction or the force will act vertically upward.

20.7 Barlow's Wheel

Peter Barlow utilised the force which acts on a current-carrying conductor in a magnetic field to produce continuous rotation. The arrangement is as shown in Fig. 20.12.

When the switch is closed, current flows down the spoke dipping into the mercury. According to Fleming's left-hand rule a force acts on the spoke at right angles to the plane of the paper and causes the wheel to rotate. The next spoke then dips into the mercury and again the force acts on it and it moves ahead. The process is repeated and results in continuous clockwise rotation of the wheel. If the direction of current is reversed, the direction of rotation of the wheel is also reversed.

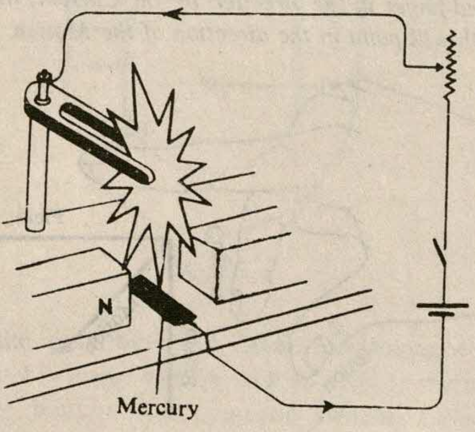


Fig. 20.12 Barlow's wheel

20.8 Electric Motor

An electric motor is a device which transforms electrical energy into kinetic energy that can do work. It is used to run fans, vacuum cleaners, egg beaters, water pumps, trains and lifts, etc. It is based upon the principle of the force acting on a current-carrying conductor in a magnetic field. The direction of motion is governed by Fleming's left-hand rule which is also sometimes named as the motor rule.

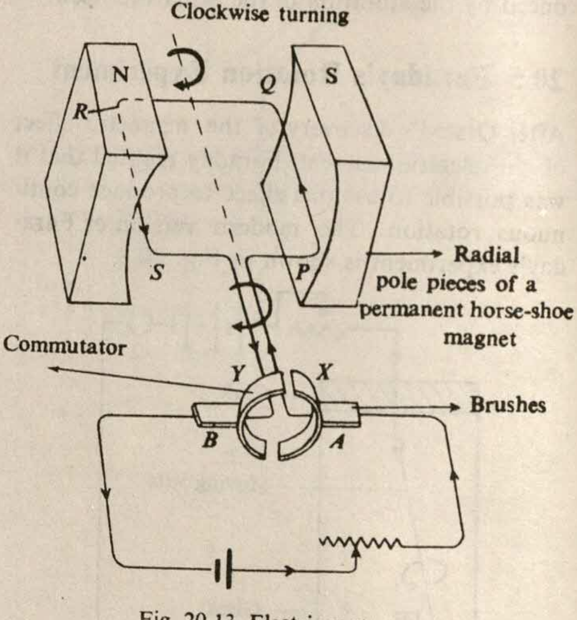


Fig. 20.13 Electric motor

Fig. 20.13 illustrates the simple direct current (d.c.) motor. It consists of a rectangular coil of insulated copper wire wound on an *armature* which can rotate about a spindle in the space between two concave cylindrical poles of a permanent magnet. The two ends of the coil are soldered to the two halves of a copper split ring called a *commutator*. Two carbon brushes are made to slightly press against the two half rings by means of springs and are joined to a battery, rheostat and a switch.

Suppose the coil is in horizontal position when the current is switched on as shown in Fig. 20.14. According to Fleming's left-hand rule a force F_1 acts on PQ vertically downward and an equal force F_2 acts on RS vertically

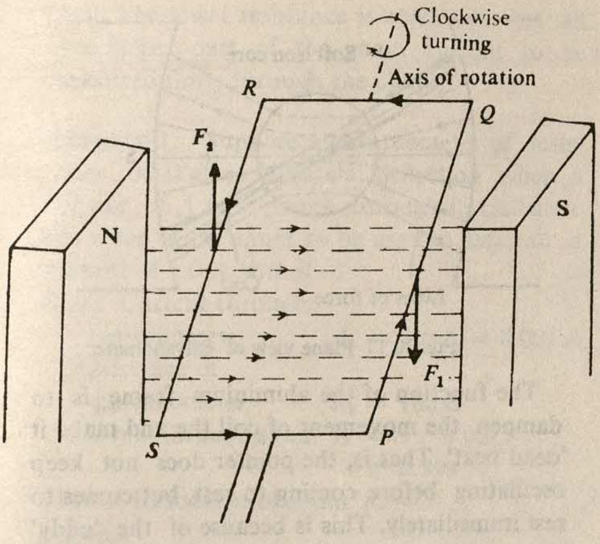


Fig. 20.14

upward. These two equal and opposite forces form a couple which turns the coil in clockwise direction until it reaches the vertical position. In this position brushes touch the space between the two halves of the commutator and the current is switched off.

Due to inertia of motion, the coil turns past the vertical position and then the half split ring X changes contact from brush A to B and Y from brush B to A. SR becomes the right-hand side and a downward force acts on it while PQ goes to the left-hand side and an upward force acts on it. These forces form a couple which keeps on rotating the coil in clockwise direction.

The simple motor as described above is not very powerful, but it can be improved by increasing the number of turns in the coil and winding them on a soft iron armature. With greater number of turns, the forces on the sides of the coil become large; and the iron armature gets magnetised which increases the strength of the field and thereby the forces on the sides of the coil.

In commercial motors a cylindrical armature is used having slots around which a number of coils are wound. Each coil has its own pair of segments on a multi-segment commutator (Fig. 20.15). This design gives increased power coupled with smooth running. Usually the magnetic field is produced by an electromagnet and the coils wound round the two arms are called field coils. The field coils are usually in series with the armature coil (series wound) and sometimes are in parallel with it (shunt wound) depending upon the use to which the motor is put.

20.9 Moving Coil Galvanometer

A galvanometer is a sensitive meter which is used to detect or measure currents. It can be either moving coil or moving magnet type. The moving coil type is based upon the motor or *Fleming's left-hand rule*.

It consists of a rectangular coil of insulated copper wire which can rotate freely in the radial magnetic field produced between the two poles of a concave cylindrical horse-shoe permanent

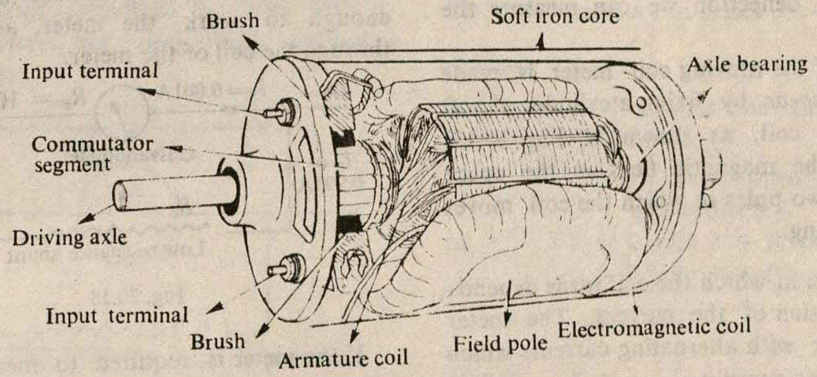


Fig. 20.15 **Commercial motor**

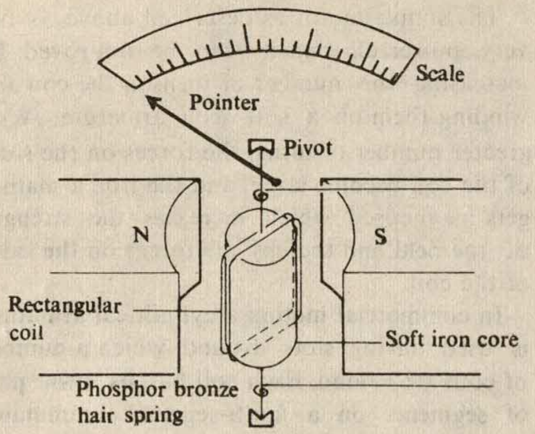


Fig. 20.16 Moving coil galvanometer

magnet. The galvanometer can be either suspension or pivoted type. In the pivoted type, the coil is wound on a light aluminium frame and its two ends are joined to pivots with jewelled bearings. It carries a pointer which moves over a scale and a soft iron cylindrical core. At each end of the coil there is a hair spring wound in opposite direction. The current enters or leaves the coil through them.

When a current passes through the coil, two equal and opposite forces act on it which form a couple that tends to rotate the coil. As the coil moves, hair springs either wind or unwind and thereby provide a controlling couple which opposes the motion of the coil. The coil turns and comes to rest when the moment of controlling couple balances the moment of deflecting couple. The amount of deflection produced depends upon the strength of the current. Thus, by measuring deflection we can measure the current.

The scale of the moving coil meter is made uniform or *linear* by fixing a cylinder of soft iron inside the coil, as shown in Fig. 20.17. This makes the magnetic field in the space between the two poles in which the coil moves uniformly strong.

The direction in which the coil turns depends upon the direction of the current. The meter will not work with alternating currents which change direction rapidly.

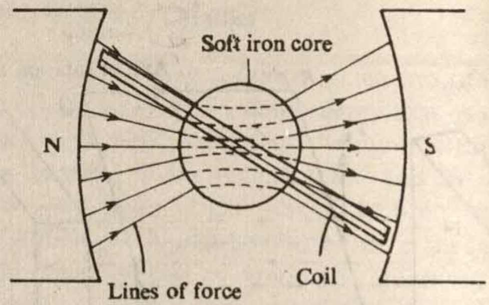


Fig. 20.17 Plane view of galvanometer

The function of the aluminium frame is to dampen the movement of coil the and make it 'dead beat'. That is, the pointer does not keep oscillating before coming to rest, but comes to rest immediately. This is because of the 'eddy' currents produced in the frame, about which you will read in a later chapter.

20.10 Conversion of Galvanometer into an Ammeter

The galvanometer is a very sensitive meter that can measure very small currents. Usually it takes 0.001 A current to make the pointer move across the scale. It has a resistance of 100 Ω. An ordinary ammeter, however, is required to measure currents of strength 1 to 2A. If this current is passed through a galvanometer, its coil will get burnt.

A low resistance called *shunt* is connected in parallel with the galvanometer to convert it into an ammeter. Most of the current to be measured takes the easy path through the shunt. Only a very small part of the current which is just enough to work the meter, actually flows through the coil of the meter.

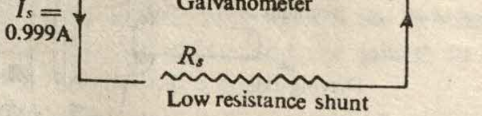


Fig. 20.18

If the meter is required to measure higher current a lower resistance shunt needs to be used. The lower resistance is needed so that an even larger part of the main current to be measured flows through the shunt.

Example 1. Suppose a galvanometer of resistance 100 Ω gives full scale deflection when a current of 1 mA passes through it. Calculate the value of the shunt to be used to measure a current of 1.0 A with it.

Given Current through
galvanometer $I_g = 1\text{ mA} = 0.001\text{ A}$
Resistance of
galvanometer $R_g = 100\,\Omega$
Current through shunt $I_s = 1 - 0.001 = 0.999\text{ A}$

To find Resistance of shunt $R_s = ?$

Solution

As galvanometer and shunt are in parallel

$$\therefore \quad \text{P.D. on shunt} = \text{p.d. on galvanometer}$$
$$\text{or} \quad I_s \times R_s = I_g \times R_g$$
$$\therefore \quad 0.999 \times R_s = 0.001 \times 100 = 0.1$$
$$R_s = \frac{0.1}{0.999} = \frac{100}{999}$$
$$= 0.1001\,\Omega \qquad \textit{Answer}$$

20.11 Conversion of a Galvanometer into a Voltmeter

A voltmeter is required to measure p.d. across a conductor and hence must be connected in parallel to it. As it is connected in parallel, its resistance must be very high. This is done by joining a high resistance in series with it. Thus voltmeters are very high resistance galvanometers.

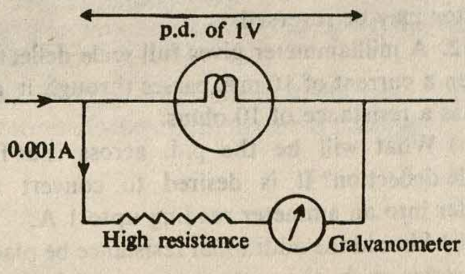


Fig. 20.19

Suppose the galvanometer, which can take a current of 0.001 A and is of 100 Ω resistance is required to read a maximum p.d. of 1 V. The metre can take a p.d. of $100 \times .001 = 0.1$ V. Hence, the p.d. on the resistance in series should be $1.0 - 0.1 = 0.9$ V. Its resistance would be

$$\frac{0.9}{0.001} = 900\,\Omega$$

The value of the resistance in series is higher when the meter is required to measure higher potential difference.

Example 2. A galvanometer of resistance 1000Ω gives full scale deflection when the current through it is 100 μA. How can you convert it to a voltmeter measuring 5 V? Draw a diagram to illustrate your answer.

Given The current which the galvanometer
can take $= 100\,\mu\text{A} = 0.0001\text{ A}$
Resistance of
galvanometer $= 1000\,\Omega$

In order to make it read 5 V, a high resistance of say X ohms is connected in series.

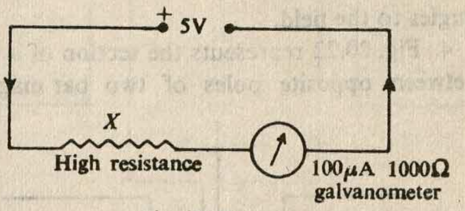


Fig. 20.20

To find Resistance in series $X = ?$

Solution

In series total p.d. is the sum of p.d. on individual resistances.

$$\therefore \quad 5\text{ V} = \text{p.d. on } X \text{ ohms} + \text{p.d. on galvanometer}$$
$$\text{or} \quad 5\text{ V} = 0.0001\,X + 0.0001 \times 1000$$
$$= 0.0001\,X + 0.1$$
$$\therefore \; 4.9\text{ V} = .0001X$$
$$\text{Hence} \quad X = \frac{4.9}{0.0001} = 49{,}000\,\Omega \qquad \textit{Answer}$$

QUESTIONS

1. Give a diagram showing the lines of magnetic force due to a current in a straight conductor, in a plane perpendicular to the conductor.

Describe an experiment to show that a current-carrying conductor which is perpendicular to a magnetic field experiences a mechanical force. Show clearly the directions of current, the magnetic field and the force.

2. In the diagrams below, draw the lines of force and mark their direction.

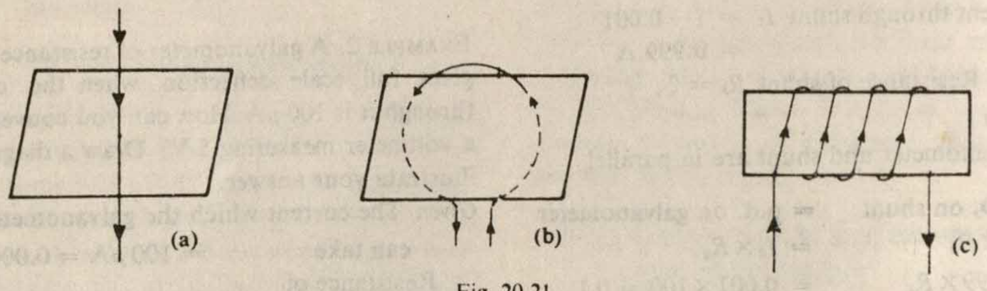


Fig. 20.21

3. State and name the rule which gives the direction of force which acts upon a current-carrying conductor placed in and at right angles to the field.

4. Fig. 20.22 represents the section of a wire between opposite poles of two bar magnets.

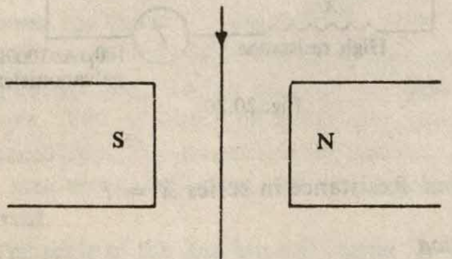


Fig. 20.22

Draw the lines of force between the poles and show on the diagram the direction of force on the wire when the current flows down the wire.

5. Draw a labelled diagram of an electric buzzer and explain how it works.

6. Draw a diagram of a single d.c. motor. Clearly mark on it the direction of supply of current and the direction of rotation of the armature. Explain the action of the motor.

7. What factors affect the strength of the force on a current-carrying wire in a magnetic field?

8. Explain how the power of an electric motor can be increased.

9. Draw a diagram of a moving coil galvanometer and explain how it works. Explain why it cannot be used to measure alternating currents.

10. Explain how a moving coil galvanometer can be converted into (a) an ammeter, and (b) a voltmeter. Illustrate your answer by drawing suitable diagrams.

11. Describe, with the aid of a labelled diagram, the structure and action of a simple two pole electric motor. Explain the action of a commutator.

Will the motor run on direct current only, on alternating current only or on both? Give reasons.

Explain how the direction of rotation of the motor may be reversed.

12. A milliammeter gives full scale deflection when a current of 10 mA passes through it and it has a resistance of 10 ohms.

(i) What will be the p.d. across it at full-scale deflection? It is desired to convert this meter into an ammeter reading upto 1 A.

(ii) Should the additional resistance be placed in series with the meter or in parallel with it?

What should be its value?

(iii) What will be the current passing through the additional resistance when the meter is showing full-scale deflection?

13. Fig. 20.23 shows a moving coil meter. Name the parts labelled *A*, *B*, *C* and *D*. Give the function of each part.

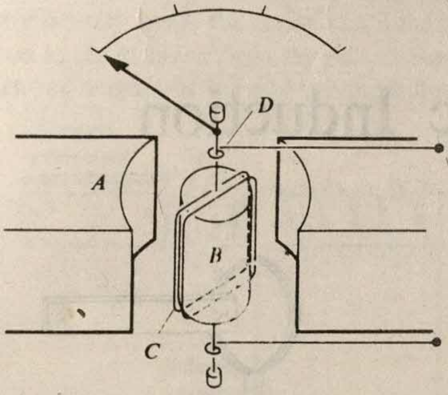
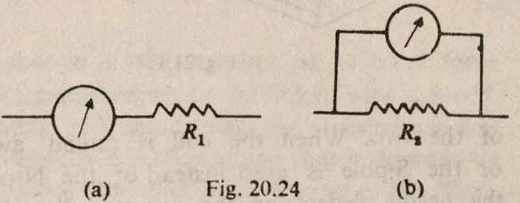


Fig. 20.23

14, Complele the following sentences:

In Fig. 20.24a the resistance R_1 is said to be in———and makes the meter a———. It is———as compared to the resistance of the meter.



(a) Fig. 20.24 (b)

In Fig. 20.24b the resistance R_2 is said to be in———and is connected in———and makes the meter into a———. It is a———resistance as compared to the resistance of the meter.

15. A moving coil galvanometer has a resistance of 40 Ω and gives a full scale deflection of 2 mA.

(a) What is the potential difference across its terminal when this current is flowing?

(b) How can this galvanometer be converted into a voltmeter reading a maximum of 2 V potential difference? Calculate the value of resistance and show by a diagram how it is connected.

(c) How can this galvanometer be changed into an ammeter reading a full scale deflection of 1 A current? Calculate the value of the resistance to be joined and show by a diagram how it is joined to the meter.

16. A voltmeter gives a full scale deflection when the potential difference between its terminals is 1 V. Its resistance is 400 Ω. How would you convert it:

(a) to give full scale deflection with a p.d. of 10 V;

(b) to work as an ammeter reading upto 250 mA.

17. Fig. 20.25 shows a coil of wire *ABCD* between the opposite poles of two separate magnets. The dotted line represents an axle about which the coil can turn. A current is passed through the coil in the direction shown. Which side of the coil will start moving upwards, out of the plane of the paper? In what position will the coil come to rest?

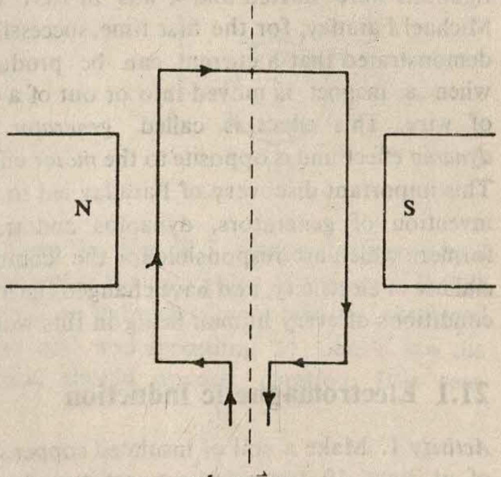


Fig. 20.25

21

Electromagnetic Induction

In 1813, Orsted discovered that an electric current produces a magnetic field. Soon many scientists started wondering whether the reverse process, i.e. the production of electric current from a magnetic field, was also possible. Investigations were started and it was in 1831 that Michael Faraday, for the first time, successfully demonstrated that a current can be produced when a magnet is moved into or out of a coil of wire. This effect is called *generator* or *dynamo* effect and is opposite to the *motor* effect. This important discovery of Faraday led to the invention of generators, dynamos and transformers which are responsible for the commercial use of electricity, and have changed the living conditions of every human being in this world.

21.1 Electromagnetic Induction

Activity 1. Make a coil of insulated copper wire of at least 10 turns and connect its ends to a centre zero sensitive galvanometer as shown in Fig. 21.1. Move the north pole of a strong bar magnet rapidly into the coil and then out of it or, alternatively, move the coil towards and then away from the magnet.

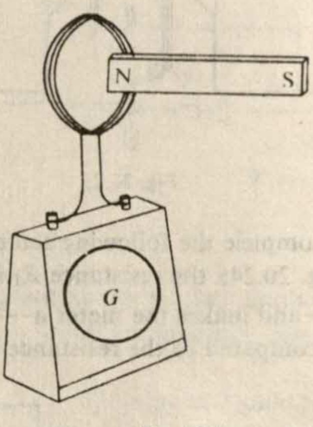


Fig. 21.1

The needle of the galvanometer deflects to one side when either the magnetic N-pole is moved towards the coil or the coil is moved towards it, showing thereby that an *induced e.m.f.* or *current* is produced. The needle comes back to zero when there is no relative motion of the two. When the coil is pulled away or the S-pole is used instead of the N-pole the needle deflects in the opposite direction, showing thereby that the direction of induced e.m.f. is reversed. It is observed that no current is induced when both the magnet and the coil remain at rest, whether the magnet is inside or outside the coil. It is further observed that when the magnet used is stronger or when it is moved more rapidly, the induced e.m.f. is greater. The e.m.f. is also seen to increase with increase in the number of turns of the coil.

(It is better to consider induced e.m.f. rather than induced current as current depends upon the resistance of the circuit while the value of induced e.m.f. is independent of the circuit.)

We may conclude that the induced e.m.f. depends upon:

1. The number of turns in the coil;
2. The strength of the magnet;
3. The speed with which the magnet is moved nearer or away from the coil.

There are lines of force around a magnet which are densest near the poles and become less dense as the distance from the pole increases. When the magnet or the coil is moved there is a change in the number of lines of force which pass through or are linked with the coil. Faraday concluded that the induced e.m.f. is produced by this change and that it depends on the rate of change of lines of force or the 'flux'. This explains why the induced e.m.f. is greater if, for example, the magnet is moved faster.

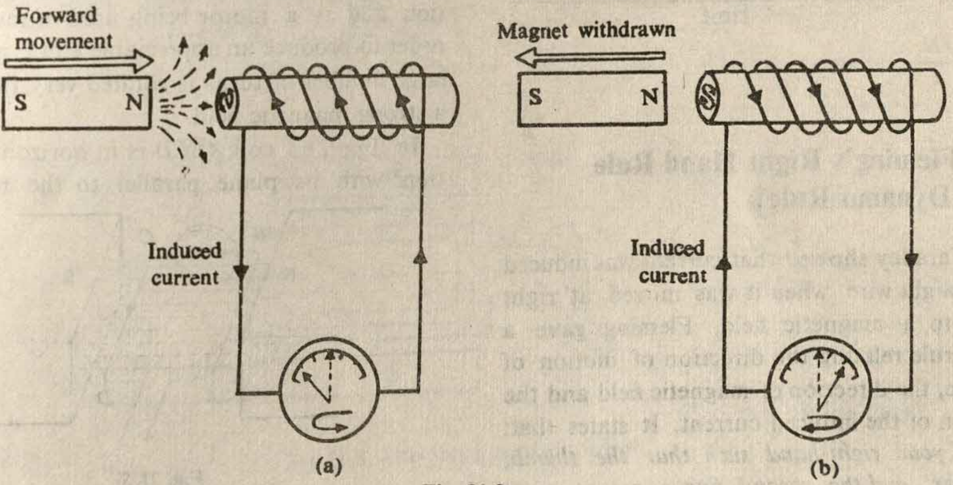


Fig. 21.2

21.2 Direction of Induced e.m.f.

This is best demonstrated by means of a magnet and a solenoid. When the N-pole of a magnet is pushed into the solenoid, an induced current is produced in it so that the end of the coil next to the magnet becomes a N-pole as shown in Fig. 21.2a. The force of repulsion tries to oppose the magnet being pushed in. Work is done against it which drives the current in the coil due to the conversion of mechanical energy into electrical energy.

When the magnet is pulled out, the induced current flows in the opposite direction so that the end of the coil becomes an S-pole. The force of attraction tries to oppose the magnet being pulled out. This is summarised as **Lenz's Law** *which states that the direction of induced current is such that it tries to oppose the motion that causes it.*

Activity 2. Wind an insulated copper wire round a piece of cork and join its two ends together as shown in Fig. 21.3. Suspend the cork by a thread within the two poles of a magnet. Rotate the cork; an induced current will be produced in the coil and according to Lenz's law the direction should oppose rotation. It is seen also that the rotation immediately slows down and the cork comes to rest. This shows that the direction of induced current is such that it opposes the effect due to which it is caused.

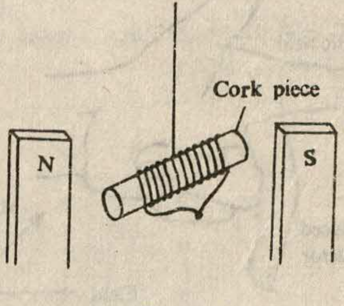


Fig. 21.3

21.3 Faraday's Law of Electromagnetic Induction

It states that whenever in any enclosed coil there is change in magnetic flux or number of lines of force linked with it, an induced e.m.f. is produced and it lasts so long as the change lasts. The magnitude of induced e.m.f. is directly proportional to the rate of change of flux linked with it.

$$\text{e.m.f.} \propto \frac{\text{change in the number of lines of force}}{\text{time}}$$

$$e \propto \frac{N}{t}$$

21.4 Fleming's Right Hand Rule (Dynamo Rule)

After Faraday showed that current was induced in a straight wire when it was moved at right angles to a magnetic field, Fleming gave a simple rule relating the direction of motion of the wire, the direction of magnetic field and the direction of the induced current. It states that: *stretch your right-hand such that the thumb, forefinger, and the second finger are at right angles to one another. If the Forefinger points in the direction of the Field and the thuMb in the direction of Motion, then the seCond finger will point in the direction of induced Current* (Fig. 21.4).

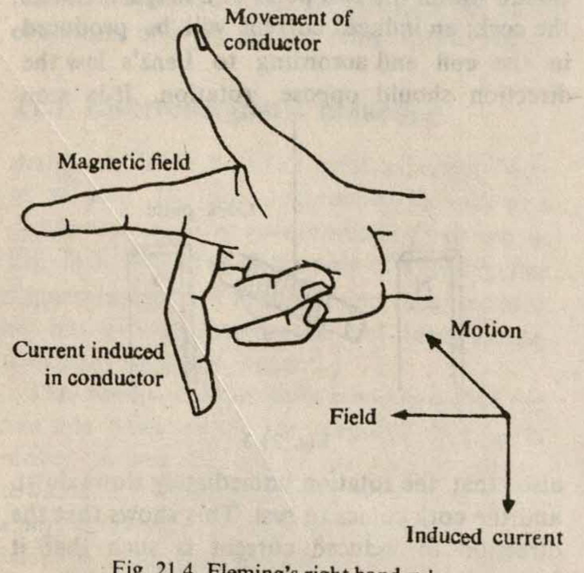


Fig. 21.4 Fleming's right hand rule

21.5 Dynamo or Generator

In a generator, a coil is rotated about its horizontal axis in a magnetic field and electricity is obtained by the conversion of mechanical energy into electrical energy. Thus, it is based upon the phenomenon of electromagnetic induction and is a motor being used in reverse. In order to produce an appreciable e.m.f a coil of large number of turns is rotated very rapidly in a strong magnetic field.

In Fig 21.5 coil *ABCD* is in horizontal position with its plane parallel to the magnetic lines of force and is rotated clockwise. This position may be called 0° position. On rotating, it cuts the magnetic field at the maximum rate, hence a maximum e.m.f. is induced. The length *AB* moves vertically upward and *CD* downward. According to Fleming's right-hand rule, in *AB* current is induced from *A* to *B* and in *CD* from *C* to *D* till the coil becomes vertical. In the vertical position or at 90°, *AB* and *CD* move parallel to the magnetic field and no current is induced in the coil.

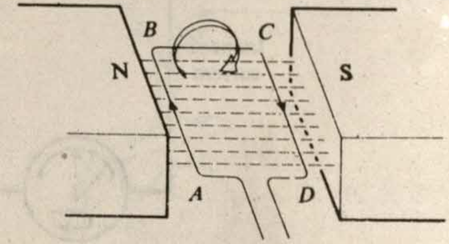


Fig. 21.5

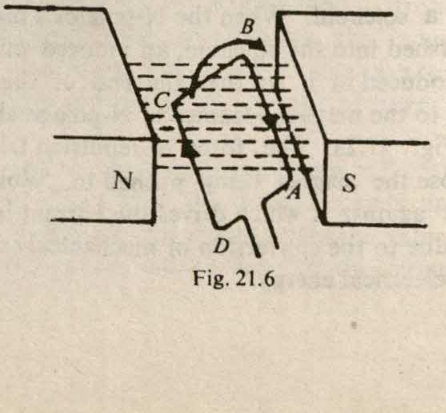


Fig. 21.6

When the wire turns beyond 90°, *AB* starts moving downward while *CD* moves vertically upward. As a result the direction of induced current is reversed. Thus from 90° to 270° rotation, the induced current in the coil is in the direction *DCBA*. From 270° to 0° (or 360°), the direction of induced current is reversed to *ABCD* again.

The current in the coil not only changes direction twice in one rotation but its magnitude also varies. It is maximum when the lengths *AB* and *CD* are moving at right angles to the field direction (i.e. in 0° and 180° positions). The induced e.m.f. or current is zero in the vertical positions of 90° and 270°. Fig. 21.7 shows how the induced current or e.m.f. in the coil varies with the rotation of the coil in the magnetic field. Such a current is called *alternating current* (a.c.) as shown in the graph of Fig. 21.7.

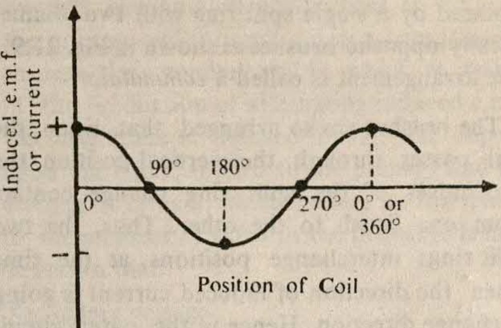


Fig. 21.7

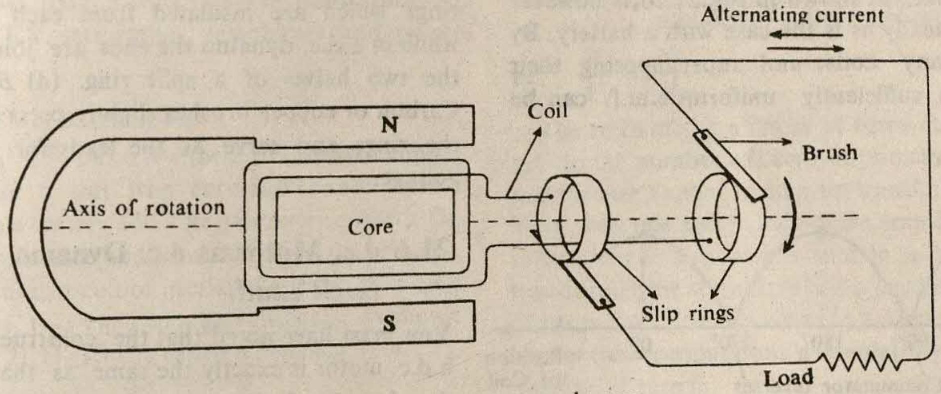


Fig. 21.8 Alternating current dynamo

In an alternating current dynamo, the coil is connected to the load (heater, motor, etc.) by means of two *slip rings* against which *carbon brushes* slightly press. These serve as leads for the output voltage. The current in the load changes in the same way as the current in the coil (Fig. 21.8).

In the direct current dynamo slip rings are

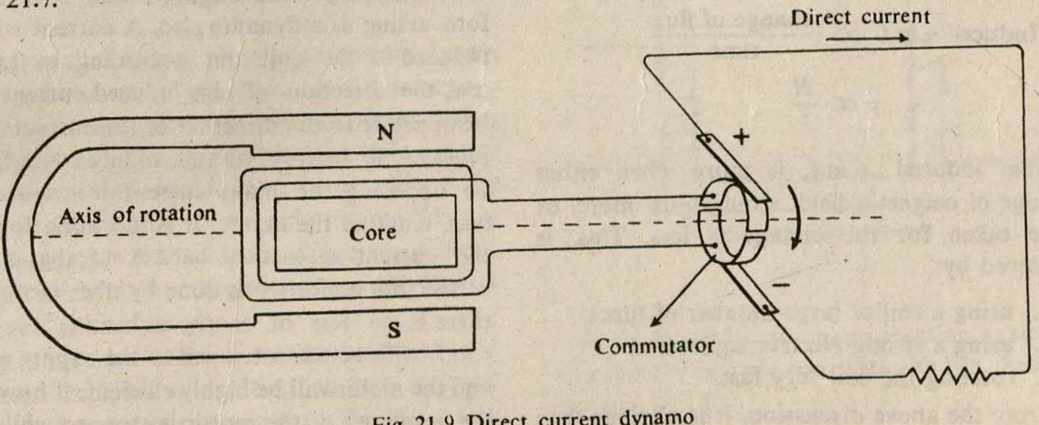


Fig. 21.9 Direct current dynamo

replaced by a single split ring with two diametrically opposite brushes as shown in Fig. 21.9. The arrangement is called a *commutator.*

The brushes are so arranged that when the coil passes through the vertical position, the two halves of the split ring change contact from one brush to the other. Thus, the two split rings interchange positions at the time when the direction of induced current is going to change direction. Hence in the outer circuit current always flows in one direction.

The e.m.f., as shown in Fig.21.10, is however not as steady as is the case with a battery. By using many coils, and superimposing their e.m.f.'s, a sufficiently uniform e.m.f. can be obtained.

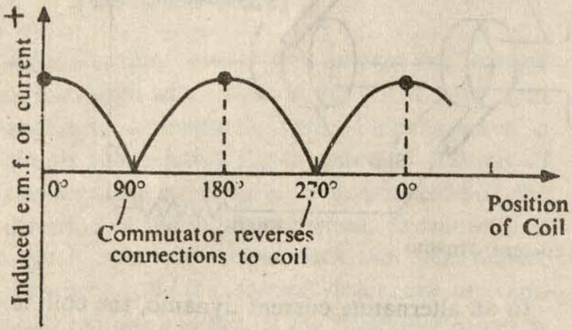


Fig. 21.10

According to Faraday's Law of electromagnetic induction the magnitude of induced e.m.f. is directly proportional to the rate of change of number of lines of force linked with the coil.

$$\text{i.e. Induced e.m.f} \propto \frac{\text{change of flux}}{\text{time}}$$

$$\text{or} \qquad e \propto \frac{N}{t}$$

The induced e.m.f. is more when either change of magnetic field strength is more or time taken for the change is less. This is achieved by:

1. using a coil of large number of turns;
2. using a strong electromagnet and
3. rotating the coil very fast.

From the above discussion, it is obvious that a generator or dynamo has four main parts: (a) *Field magnet*: In an ordinary dynamo like a cycle dynamo, it is a permanent horse-shoe magnet with concavo-cylindrical poles while in a powerful dynamo, it is an electromagnet with *field* coils. (b) *Armature*: It consists of one or more coils of insulated copper wire which are wound on an iron core capable of rotation about a horizontal axis. Greater the number of coils steadier is the current generated. (c) *Slip rings* or a *split ring*: In an a.c. generator, ends of coil are soldered to two separate slip rings which are insulated from each other, while in a d.c. dynamo the ends are joined to the two halves of a split ring. (d) *Brushes*: Carbon or copper brushes slightly press against the rings and serve as the leads for output voltage.

21.6 d.c. Motor as d.c. Dynamo—Back e.m.f.

You must have noted that the construction of a d.c. motor is exactly the same as that of a d.c. dynamo. A d.c. dynamo can therefore be used as a motor and a motor as a dynamo. The only difference between the two is that in a dynamo mechanical energy of the rotating coil is converted into electrical energy supplied to the external circuit, while in a motor electrical energy supplied from outside is converted into mechanical energy of the coil.

When we pass current into a motor, the coil starts rotating in the magnetic field. It is therefore acting as a dynamo also. A current will be induced in the coil and according to Lenz's law, the direction of this induced current will be opposite to the direction of the current supplied by the battery. As this induced e.m.f. will be opposing the main current, it is called the *back* e.m.f. of the motor. It is the work done by the current against the back e.m.f. that is converted into useful work done by the motor. If there is no loss of energy in heating, the back e.m.f. will be almost equal to the supply e.m.f. and the motor will be highly efficient. If however, the armature of the motor is stopped while the current is still on, the entire electrical energy will be converted into heat in the coils which are likely to be damaged.

21.7 Transformers

A transformer is a device which is used to convert an alternating potential difference into either a lower or higher alternating p.d. The former is called a *step-down* and the latter a *step-up* transformer. The world's first transformer was made by Michael Faraday in 1831 and now we have a wide range of transformers in use in T.V. sets, radios, telephones and power houses.

Principle of a Transformer

Activity 3. Wind a few turns of insulated copper wire on a soft iron core and connect its two ends to a battery and a key (*primary circuit*). On the same core and insulated from the primary, wind another coil of insulated copper wire and join its two ends to a galvanometer as shown in Fig. 21.11. This is called a *secondary coil.*

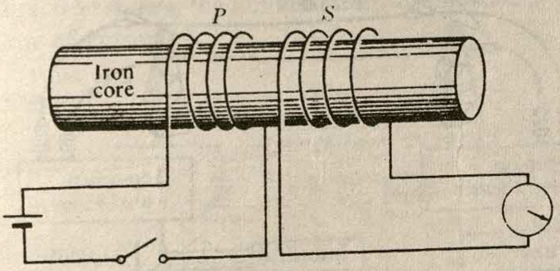


Fig. 21.11

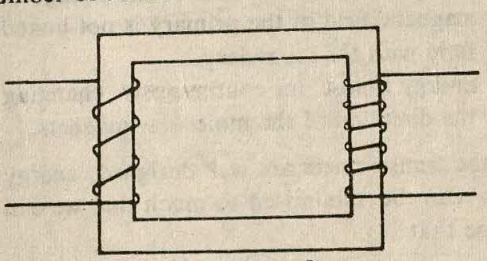
Put in the key to complete the primary circuit; the pointer of the galvanometer momentarily deflects to one side. Break the circuit by taking out the key; the pointer momentarily deflects on the opposite side. It remains at zero while either no current or a steady current flows in the primary. The deflections are very much larger when the number of turns in the secondary coil are increased.

Although two coils are sometimes operated in this fashion, alternating current is more commonly used in the primary. Then a continuously changing magnetic field is set up in the primary and through the iron core it passes through the secondary coil in which it results in the production of alternating induced e.m.f. The magnitude of induced e.m.f. will depend upon the e.m.f. applied to the primary and the number of turns in the secondary as compared to the number of turns in the primary. It may be shown that:

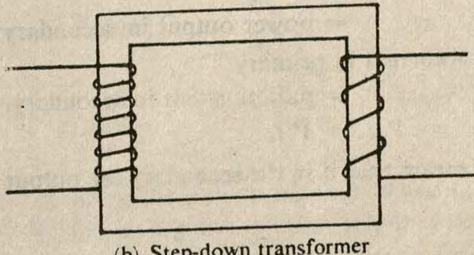
$$\frac{\text{Secondary voltage}}{\text{Primary voltage}} = \frac{\text{number of turns in secondary coil}}{\text{number of turns in primary coil}}$$

or $$\frac{V_s}{V_p} = \frac{N_s}{N_p}$$

The ratio of the number of turns in secondary to the number of turns in primary is called *transformer's ratio.* In step-up transformers it is more than one and in step-down transformers it is less than 1. This means that in a step-down transformer the secondary has a smaller number of turns than primary while in a step-up transformer the secondary has a comparatively larger number of turns.



(a) Step-up transformer



(b) Step-down transformer

Fig. 21.12

A schematic diagram representing a step-up transformer with turns ratio 3 : 1 is shown in the Fig. 21.13.

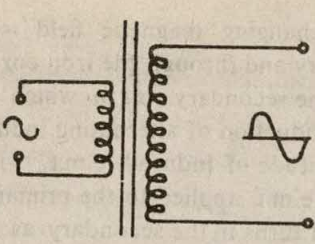


Fig. 21.13

In a transformer energy is lost in three ways:

1. *Heating* of the wire of the coils. This is reduced by using coils of thicker copper wire so that their resistance is less.
2. The changing magnetic field not only induces the current in the coil, but also in the iron core. The currents induced in the iron core are called *eddy currents* and they heat the iron core. Eddy currents are reduced by using a *laminated* iron core. This is made of laminos or thin sheets of soft iron separated by layers of varnish to stop the eddy currents from flowing. If the secondary is not perfectly linked with the primary, then whole of the change of magnetic field in the primary is not linked fully with the secondary.
3. Energy is lost in continuously changing the direction of the molecular magnets.

If the transformers are well designed, energy losses can be minimised so much that we can assume that

Power input in primary

= power output in secondary

or p.d. × current in primary

= p.d. × current in secondary

or $V_pI_p = V_sI_s$

This means that if in the secondary the output potential is high then current in it is low and vice versa.

21.8 Power Transmission

Power is transmitted from power stations to cities and industries over long distances by overhead or underground cables. Some of the power is lost in heating the cables. The power loss is given by

Power lost = resistance × current^2 = I^2R

or Power lost $\propto I^2$

and Power carried by cables

= potential difference × current

= VI

Power lost in the cables is insignificant if the current is very low. For a given power, current is low if voltage is very high. At the generating station a step-up transformer is used to increase V to reduce I for transmission along the cables. Usually, in cables power is carried at a p.d. of 132,000 volts. Before being distributed for use in houses and offices etc., a step-down transformer is used to convert it back to 220 volts.

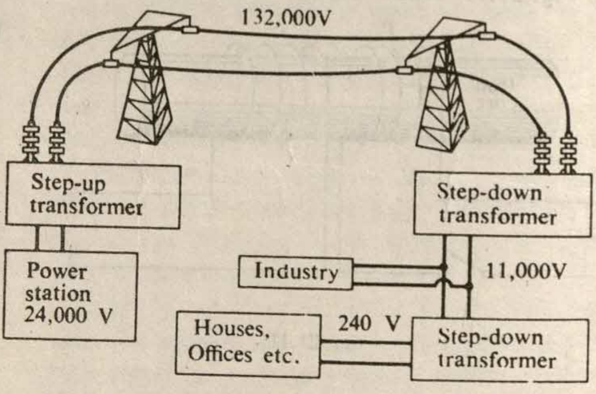


Fig. 21.14

QUESTIONS

1. Explain the term electromagnetic induction and induced electromotive force. You are given a centre zero galvanometer, a coil of insulated copper wire and a bar magnet. How

will you use them to demonstrate electromagnetic induction? Explain the law which determines the direction of induced current.

2. Fig. 21.15 shows a bar magnet being used to induce current in a coil. The magnet is slowly moved into the coil and the galvanometer *G* records a steady current. Describe any changes that would occur when:

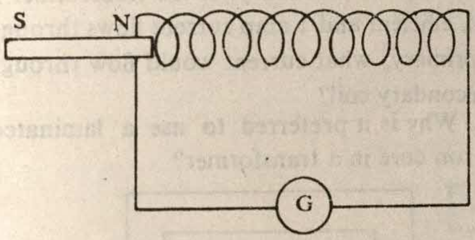


Fig. 21.15

(i) The speed of the magnet is increased.

(ii) A coil with more turns is used instead.

(iii) The direction of motion of the magnet is reversed.

(iv) The magnet stops moving.

3. In Fig. 21.16, if the wire is moved in the direction shown, the milliammeter will indicate a flow of current.

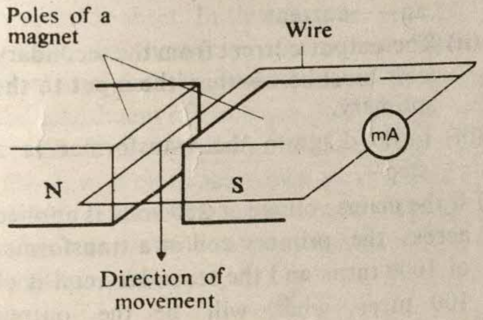


Fig. 21.16

(i) State two factors which determine the size of the current.

(ii) State two ways by which the direction of the flow of current could be reversed.

(iii) Name and state the law which indicates the direction of flow of current. In which direction will the current flow when the wire is moved as shown in the diagram.

4. The ends of a straight wire are connected to a galvanometer and then the wire is held between the poles of a horse-shoe magnet.

(a) In which direction should it be moved so that

(i) the induced e.m.f. is maximum;

(ii) the induced e.m.f. is zero?

State and name the rule which indicates the direction of induced e.m.f.

(b) What effect will the change in the speed of motion of wire have on the induced e.m.f.?

5. Explain the working of a d.c. dynamo with the help of a labelled diagram. On what factors does the e.m.f. generated in it depend?

6. What is a.c.? In which respects is it different from d.c.? What type of e.m.f. is produced when a rectangular coil with its axis perpendicular to a magnetic field is rotated in it? How does a commutator in an a.c. dynamo change a.c. of the armature into d.c. in the external circuit? Draw a labelled diagram of the d.c. dynamo and the e.m.f. produced.

7. Describe the construction of a generator and draw a labelled diagram. Explain its action.

8. Fig. 21.17 shows a simple a.c. generator.

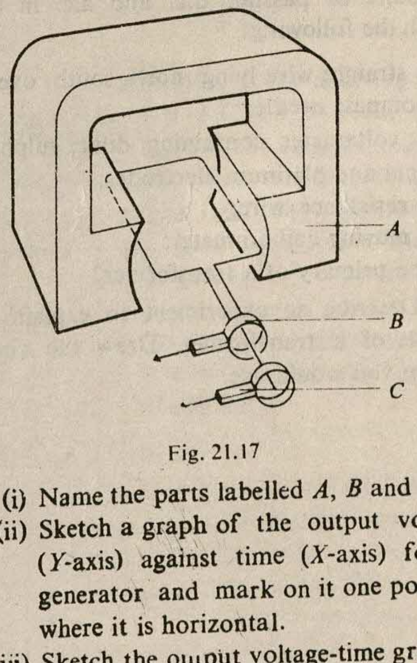


Fig. 21.17

(i) Name the parts labelled *A*, *B* and *C*.

(ii) Sketch a graph of the output voltage (*Y*-axis) against time (*X*-axis) for the generator and mark on it one position where it is horizontal.

(iii) Sketch the output voltage-time graph if split ring commutator is used.

(iv) Suggest one reason why electromagnets are preferred to permanent magnets for most generators.

9. How can a d.c. dynamo work as a d.c. motor? What is back e.m.f.? Why does it become zero when the armature stops rotating? What will happen if the armature is not allowed to rotate while the supply is still on.

10. What is the main advantage of a.c. over d.c. in supplying power from a far off power station?

11. Describe the construction and working of a step-up transformer. Illustrate your answer by drawing a labelled diagram. Why is voltage stepped up for transmission over long distances and then stepped down for domestic consumption?

12. Describe the various ways by which energy is lost in a transformer. How can the losses be minimised?

13. Find the power wasted in transmission cables of resistance 0.05 when 100 kW is transmitted at (i) 200 volts. and (ii) at 20,000 volts.

14. What are the differences and similarities in the results of passing d.c. and a.c. in turn through the following:

(i) a straight wire lying north-south over a compass needle;
(ii) a voltameter containing dilute sulphuric acid and platinum electrodes;
(iii) a resistance wire;
(iv) a moving coil ammeter;
(v) the primary of a transformer?

15. Describe an experiment to explain the principle of a transformer. Draw the circuit diagram you would use.

16. A transformer has 100 turns in the primary and 500 turns in the secondary. An alternating current from a 12 V supply is applied to the primary. What is the value of voltage induced in the secondary? If the transformer is 100% efficient and 1 amp current flows through the primary, what current would flow through the secondary coil?

17. Why is it preferred to use a laminated soft iron core in a transformer?

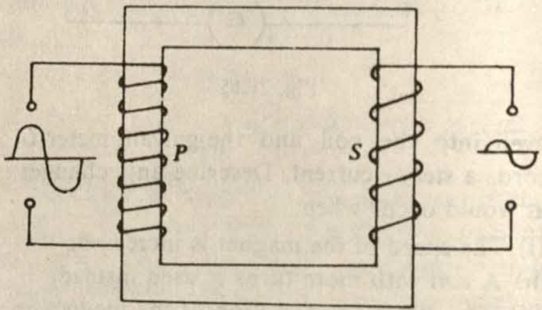


Fig. 21.18

18. Fig. 21.18 shows a simple transformer.

(a) Complete the following sentences:

(i) The input to the primary coil must be an——current.
(ii) The output current from the secondary coil must be——than the input to the primary.
(iii) In the diagram the transformer is a step——.

(b) If the mains voltage of 250 volts is applied across the primary coil of a transformer of 1000 turns and the secondary coil is of 100 turns, what will be the output voltage?

22

Electrons

Without our realising it, electrons play a very important part in our daily life. When on the move in wires electrons carry energy to do thousand and one different jobs, e.g. they light and heat our homes: operate refrigerators, fans, washing machines and record players, etc. A beam of electrons paints a scene on a television screen and can magnify a tiny object million times in an electron microscope. A more intense beam can drill a hole in less than a second in a metallic sheet. In this chapter, you will learn about the discovery of electrons; emission of electrons and the production of X-rays by the bombardment of electrons on a heavy metallic target. You will also learn the ways to control the flow of electrons which has enabled man to rectify alternating current and amplify weak signals for a wide variety of uses in electronic communication.

22.1 Cathode Rays

Air is normally an insulator but its insulation breaks down at very high potential differences. A potential difference of about 20 kV is required to pass an electric discharge through a 1 cm wide air gap. But at pressures as low as 10^{-3} cm of mercury a potential difference of 3-5 kV is sufficient to produce a discharge.

Take a discharge tube with aluminium electrodes at its opposite ends and an inside pressure of 10^{-3} cm of mercury. On applying a high potential difference of 3-5 kV a stream of electrons is emitted from the cathode and travels towards the anode with a very high velocity of 1/10th the velocity of light. These electrons strike the walls of the glass tube around the anode and emit a blue or greenish glow due to fluorescence produced in the minerals present in glass. The stream of electrons produced at the cathode and travelling towards the anode at a high speed are known as **cathode rays**.

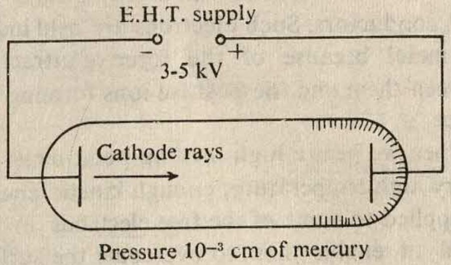


Fig. 22.1

Nature of Cathode Rays

A cathode ray consists of a beam of fast moving electrons. The mass of each particle is 9.11×10^{-31} kg which is about 1/1840 of the mass of a hydrogen atom and the charge on each particle is -1.6×10^{-19} coulomb. They travel with a speed of about 3×10^{7} m/s; the speed can be altered by changing the p.d. between two electrodes.

These experiments are unsuitable for repetition in schools because:

1. a high voltage of 30 kV is employed;
2. dangerous X-rays are emitted;
3. the observations are sometimes difficult to interpret.

Nowadays hot metal filaments are used which employ low voltages of under 5 kV so that X-rays are not produced.

22.2 Thermionic Emission

Metals contain a large number of such electrons which are free to move within it and are called *free or mobile electrons*. This is why metals are good conductors. Such electrons are held inside the metal because of the force of attraction between them and the positive ions forming the lattice.

When we heat a high melting point metal to a very high temperature, enough kinetic energy is supplied to some of the free electrons in the metal to enable them to overcome the surface barrier and fly off from the surface into space as free electrons in the same manner as liquid molecules boil off from a hot liquid.

The temperature at which the evaporation of electrons becomes perceptible depends upon the force of attraction between the free electrons and the positive ions forming the lattice and is different for different metals. The rate of emission is fast for cesium, slower for tungsten and quite slow for platinum. *The phenomenon of emission of electrons from the surface of a hot metal is called* **thermionic emission.** The easy way to heat a thin metal filament of a high melting point (tungsten) is to pass a current of few milliamperes through it by connecting it to a 6 V a.c. or d.c. supply.

We can show that these thermionically emitted electrons exist by enclosing a filament *C* in a glass container from which most of the air has been removed. The electrons then do not collide with air molecules and hence do not get slowed down. Another metal plate *A* is enclosed a short distance away from *C* to attract electrons across to it (Fig. 22.2) by connecting it to the positive pole of a battery, the negative of which is connected to the filament.

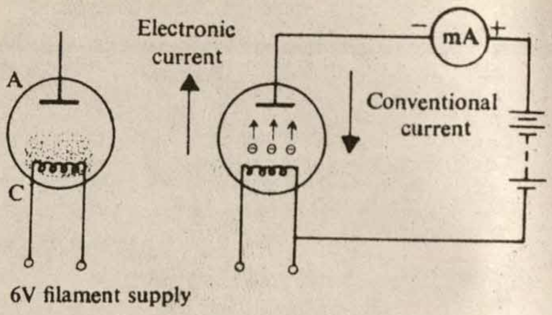


Fig. 22.2 Thermionic emission

When the filament gets heated, emitted electrons cluster around it in the form of a cloud known as *space charge*. On connecting plate *A* to the positive terminal of a battery and plate *C* to the negative terminal, electrons are attracted towards *A*. The space between *A* and *C* becomes conducting and current flows which can be detected by a milliammeter. The electrons flow from the filament to the anode while the conventional current flows from the anode to the filament.

22.3 The Electron Gun

The electron gun is a device which is used to obtain a beam of electrons. It is shown in Fig. 22.3.

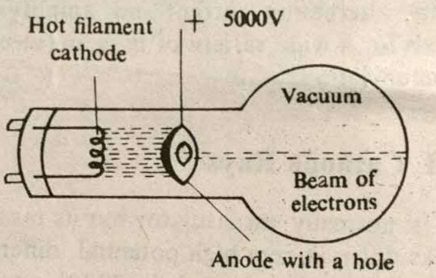


Fig. 22.3 Electron gun

The electrons emitted by the hot filament are attracted to the anode and are accelerated towards it. By the time electrons reach the anode, they become so fast that some of them pass straight through the hole and keep moving with the same speed. In this way a beam of fast moving electrons is produced. The velocity of electrons depends upon the p.d. between the anode and the cathode.

22.4 Cathode Ray Tube

The cathode ray tube is the main component of a cathode ray oscilloscope, television set or a radar. Fig. 22.4 shows in a simplified way the chief features of a cathode ray tube.

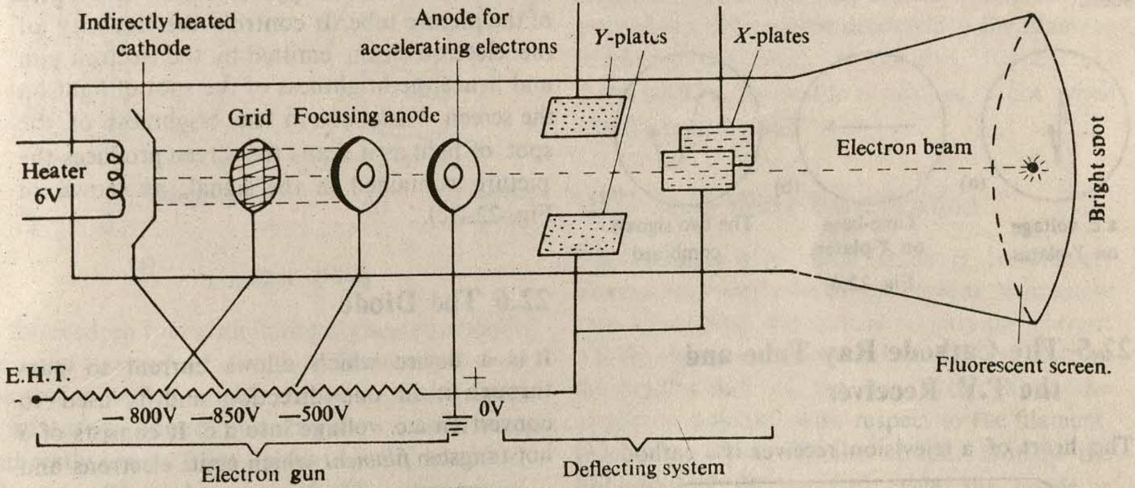


Fig. 22.4 Cathode rays tube

1. *Electron gun.* It emits a beam of electrons and consists of an indirectly heated cathode followed by a grid and a series of ring-like anodes. The rate of electrons passing the grid increases by making it less negative; this in turn makes the spot on the screen more bright. The high positive potentials on the anodes with respect to the cathode not only accelerate the electrons but also focus them into a fine beam.
2. *Deflection system.* It consists of two pairs of deflecting plates. The Y-plates deflect the beam and thereby the spot vertically and the X-plates deflect it horizontally.
3. *Flourescent screen.* The screen at the end of the tube is coated with a mixture of flourescent material (e.g. zinc sulphide) and phosphorent material (e.g. calcium phosphate). The latter is responsible for the 'after glow', i.e. the glow which continues for a while even when the electrons have moved to a different part of the screen. This after glow combined with the rapid movement of the spot gives a continuous trace.

Operation of Cathode Ray Tube

Y-plate deflection. When the upper Y-plate is made positive, the electron beam is deflected upward and when the upper plate is made negative the spot moves downward. The distance through which the spot moves is directly proportional to the p.d. between the two Y-plates. When an a.c. potential is applied to the Y-plates, the spot moves up and down 50 times a second making a straight line trace. The length of the trace above the mean position is the measure of the maximum potential Fig. 22.5.

X-plate deflection. Potential difference applied on X-plates deflects the electron beam in X-direction; it moves the spot to the left or the right. In the oscilloscope a time-base circuit is introduced on X-plates, which uniformly builds up

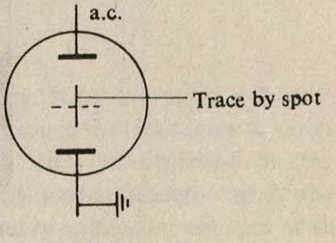
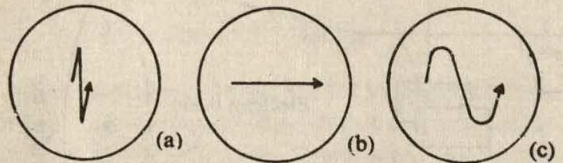


Fig. 22.5

potential difference with time to a maximum and then suddenly drops and repeats the process at regular intervals. Due to this, the spot moves horizontally across the screen with steady velocity, flies back to zero and repeats the cycle continuously.

When a signal is applied to the Y-plates, the time-base spreads it out along the X-axis so that the vibration of the signal with time can be seen.



a.c. voltage on Y-plates

Time-base on X-plates

The two signals combined

Fig. 22.6

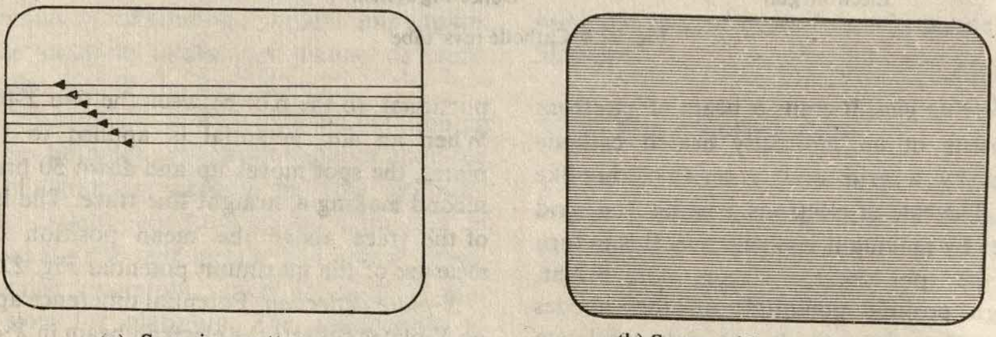
22.5 The Cathode Ray Tube and the T.V. Receiver

The heart of a television receiver is a cathode ray tube, commonly called a **picture tube.** The electron beam produced by the electron gun is made to **scan** the entire TV screen horizontally as shown in Fig. 22.7(a), by means of **sweep currents** supplied to the deflection coils. As the bright spot moves across the screen at a high speed we observe the pattern shown in Fig. 22.7(b) on account of persistence of vision.

The **video signal** (or picture signal as it is commonly called) is supplied to the control grid of the picture tube. It controls the intensity of the electron beam emitted by the electron gun and hence the brightness of the spot of light on the screen. Variations in the brightness of the spot of light as it scans the screen produces the picture contained in the signal, as shown in Fig. 22.7(c).

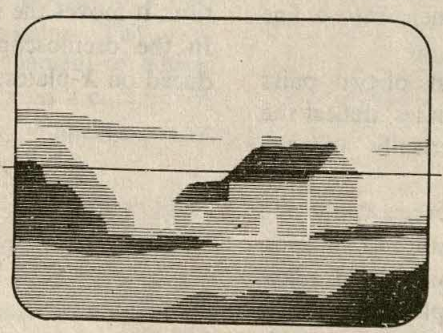
22.6 The Diode

It is a device which allows current to pass through it in one direction and is used to convert an a.c. voltage into d.c. It consists of a hot tungsten *filament* which emits electrons and



(a) Scanning pattern

(b) Screen with no video signal



(c) Screen with signal controlling intensity of bright spot

Fig. 22.7

is surrounded by a second plate called *anode.* Both are mounted in an evacuated glass envelope. Being a two-electrode vacuum tube, it is called a **diode** and since it allows electricity to pass in one direction only, it is named a **diode valve**.

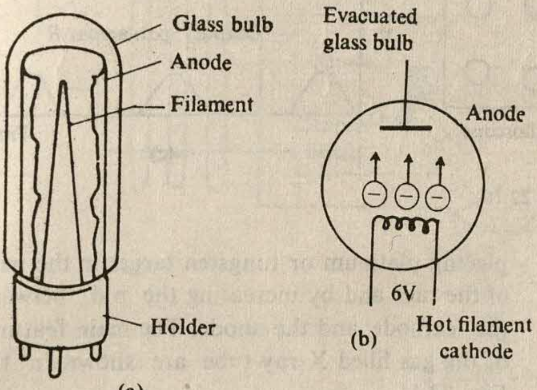


Fig. 22.8 Diode

In modern tubes, an indirectly heated cathode is used instead of the hot filament. It consists of a hollow nickle cylinder coated with a mixture of barium and strontium oxides. It is indirectly heated from inside by an insulated filament. The advantage of this arrangement is that the cathode emits electrons in large numbers at a relatively low temperature and the fluctuations in filament current do not substantially affect the emission of electrons.

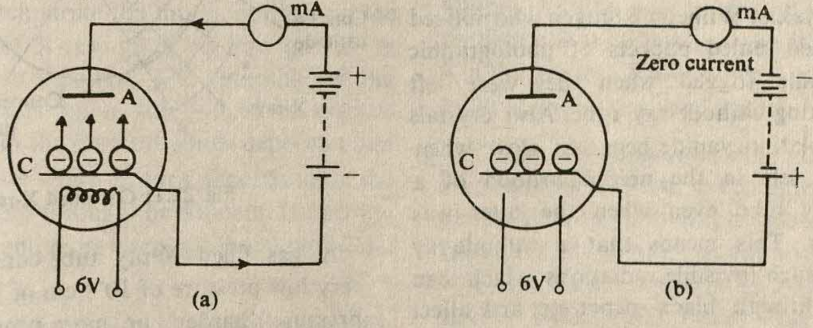


Fig. 22.9

When we attach the anode A to the positive terminal of a battery and the cathode C to the negative terminal, electrons are attracted by the anode and a current flows in the plate or anode circuit as shown by the milliammeter (Fig. 22.9a). Since the battery drives electrons from negative to positive, the electrons must have travelled from the filament to the anode through the space between the two electrodes.

When the diode is connected in the reverse way (Fig. 22.9b) with the anode connected to the negative terminal of the battery and the cathode to the positive, no current flows. This is because the electrons are now repelled by the negative anode. We may conclude that current only flows through the diode when the filament is hot and the anode is positive. No current flows whether the anode is positive or not when the filament is cold.

22.7 Half-Wave Rectification

The main use of a diode value is to convert alternating current to direct current. You know that alternating current is a varying current which changes direction (Fig. 22.10b). During the positive half of the a.c. cycle, when the anode is positive with respect to the filament, the current flows in the circuit. During the negative half of the a.c. cycle, the anode is negative with respect to the cathode and so no current flows. The p.d. across resistance R is also zero. Thus, the current in the circuit flows in one direction only. It is, however, not constant and the p.d. across the resistance R varies as shown in Fig. 22.10c, as observed on the oscilloscope. Since V varies directly as I, the current through the resistor also changes with time in exactly the same way as the p.d. across

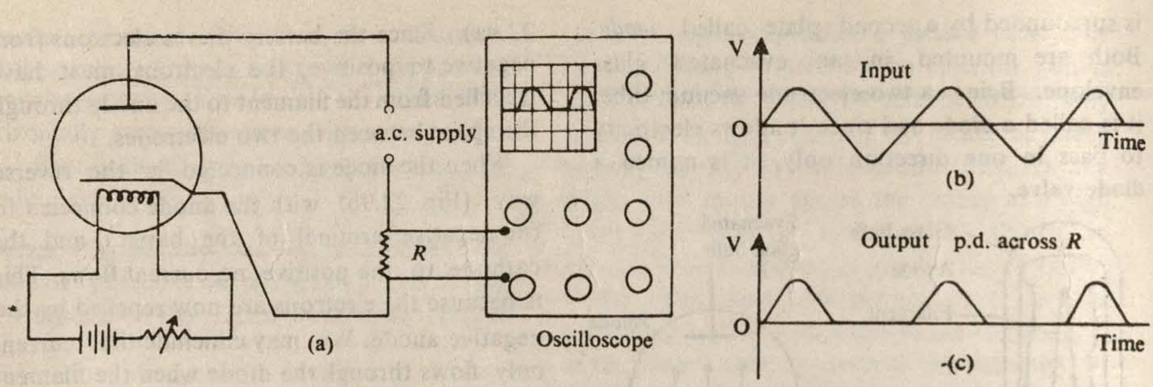


Fig. 22.10

resistor R.

We have thus changed a.c. to d.c. This process is called *half-wave rectification* as the current flows for only half the cycle.

22.8 X-Rays

When high speed energetic electrons in a cathode ray tube or a diode hit the screen or a plate, most of their kinetic energy is lost and they then become relatively slow. Most of their kinetic energy is changed into heat at the place of impact and a fraction of it is converted into a penetrating radiation known as X-rays or Röntgen rays.

These rays were first discovered in 1895 by the German physicist Wilhelm Röntgen who noticed that wrapped sealed packets of photographic plates become fogged when they were left near a working cathode-ray tube. Also crystals of barium platinocyanide began to glow when they were left in the neighbourhood of a cathode ray tube even when the latter was covered up. This means that a cathode ray tube emits such invisible radiations which can penetrate through black paper etc. and affect photographic plate, and produce flourescence Röntgen tried to find their nature but could not do so; hence he named them *X-rays*. To honour the discoverer they are also often called *Röntgen rays*.

The source of X-rays was traced to the flourescent walls struck by the cathode rays. More intense and penetrating rays were obtained by placing platinum or tungsten target in the path of the rays and by increasing the p.d. between the cathode and the anode. The main features of the gas filled X-ray tube are shown in the Fig. 22.11.

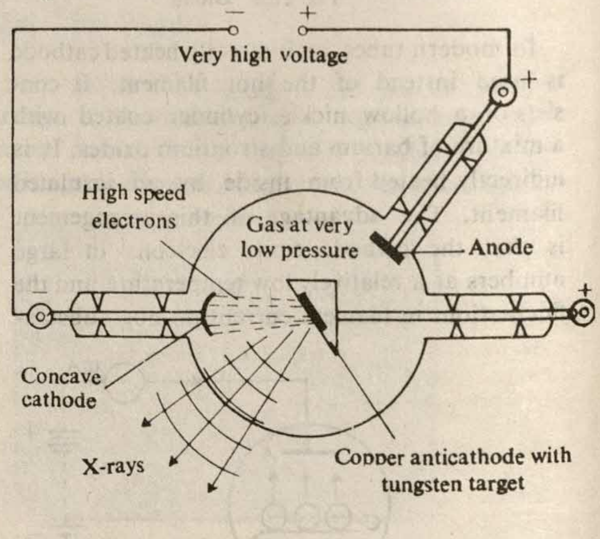


Fig. 22.11 Gas filled X-ray tube

A gas filled X-ray tube consists of air at a very low pressure of 10^{-3} cm of Hg. Lower the pressure 'harder' or more penetrating are the X-rays. The cathode is concave shaped and electrons emitting from it are focused on a tungsten target embedded in a copper block (anticathode) which ends into a copper tube to conduct away the heat produced due to the impact of electrons on the target. The target is inclined at an angle of about 45° to the rays.

In this type of tube it is difficult to control

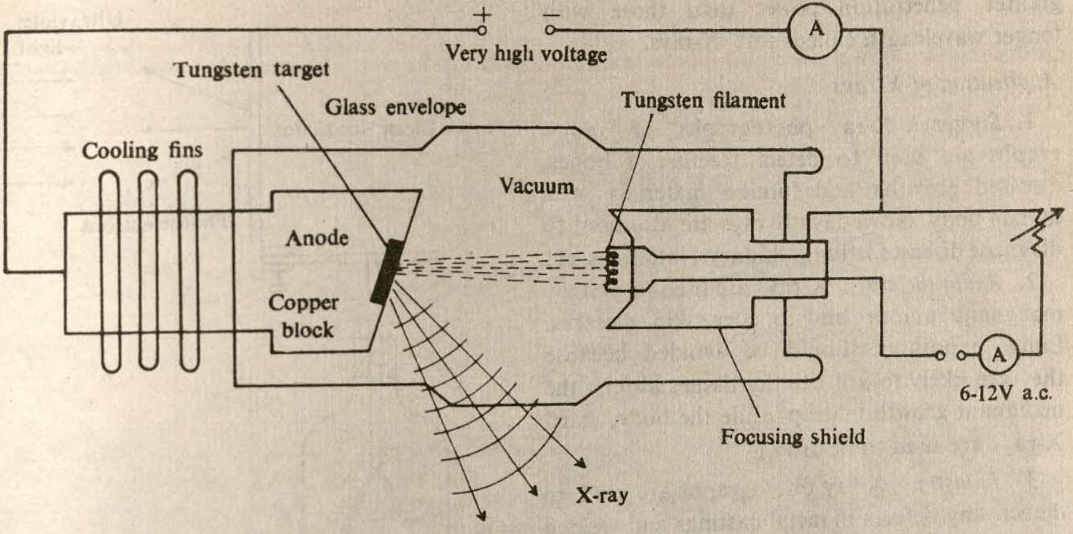


Fig. 22.12 Coolidge X-ray tube

the wave length of X-rays obtained. In the modern tubes designed on the pattern of the tube devised by W.D. Coolidge, thermionic emission is employed to produce a beam of electrons.

A heated tungsten filament acts as an electron source. The filament cup of the shield focuses electrons on to the target and the potential difference between the two electrodes speeds them up. Higher the p.d. faster are the electrons which strike the target, smaller is the wavelength of X-rays given off and greater is their penetration power. The intensity of the X-rays depends upon the rate of emission of electrons from the filament which depends upon its temperature which in turn depends upon the current flowing through the filament. Higher the filament current, more intense is the X-ray beam.

Properties of X-rays

X-rays cause *flourescence* in certain materials, e.g. zinc sulphide, barium platinocyanide and zinc tungstate. A screen coated with such a material is used as a viewing screen.

They travel along *straight lines* and can *penetrate* through wood, leather, flesh and thin aluminium sheets and are stopped by dense materials like bones and metallic articles. Penetration power of X-rays is inversely proportional to the density of the material. When a hand is interposed between a source of X-rays and a flourescent screen, a shadow is cast on the screen. In the shadow, bones are clearly visible because they are more opaque to X-rays than the flesh.

X-rays *ionise* the gas through which they pass. They knock out some electrons from the atoms of the gas and thereby render it conducting.

In small doses X-rays *kill diseased tissues* leaving healthy ones unharmed. Long exposure to X-rays is injurious because it even kills the healthy tissues. This is why X-ray tubes are encased with dense lead sheets.

X-rays affect *photographic plates* like light. Photographs can be taken either by replacing the screen with photographic plate or by directly taking the photograph of the screen.

X-rays are *not deflected* by a *magnetic* or an *electric* field. This proves that they are not charged particles.

Nature of X-rays

X-rays are electromagnetic waves of very short wavelength of the order of 10^{-10} m. Like light they can be reflected, refracted, dispersed and polarised. X-rays of comparatively smaller wavelength are called 'hard' X-rays. They possess greater penetration power than those with longer wavelength called 'soft' X-rays.

Application of X-rays

1. *Surgery* : X-ray photographs or radiographs are used to detect fracture of bones, diseased growths and foreign materials in a human body. Nowadays X-rays are also used to diagnose diseases in lungs, kidneys, intestines, etc.

2. *Radio therapy* : X-rays are used to destroy malignant tumours and to cure skin diseases. Long exposures should be avoided because they are likely to kill healthy tissues also. If the malignant growth is deep inside the body, hard X-rays are used to destroy it.

3. *Industry* : X-ray photographs are used to detect any defects in metal castings and welded joints and any cracks in the body of aeroplanes and cars.

They are also used in such diverse fields as detection of the presence of pearls in oysters and testing the uniformity of insulating materials and the quality of oil paintings. The technique used in the latter depends upon the fact that pigments containing lead compounds absorb X-rays more strongly than these which contain less dense elements.

(d) *Detective departments* : X-rays are used to detect the smuggling of precious metals, explosives, opium etc. in mail parcels and leather bags. They are also used for security checks.

(e) *Research* : X-rays are used in research to study the structure of crystals, arrangement of atoms and molecules in matter and its impact on different materials.

22.9 The Photoelectric Effect

In the year 1888, Wilhelm Hallwachs discovered that if ultraviolet light is made to fall on a clean zinc plate connected to a negatively charged electroscope, the divergence of the electroscope leaves decreases showing thereby the loss of charge.

This can be explained by concluding that when ultraviolet light falls on the zinc plate, mobile electrons absorb energy. Some of them absorb enough energy to escape from the surface. The plate acquires positive charge due to loss of electrons and neutralizes the negative charge present on the leaves. *The emission of electrons from a metal surface when light falls on it is called* **photoelectric emission;** *such electrons are called* **photoelectrons** *and the process is called* **photoelectric effect.**

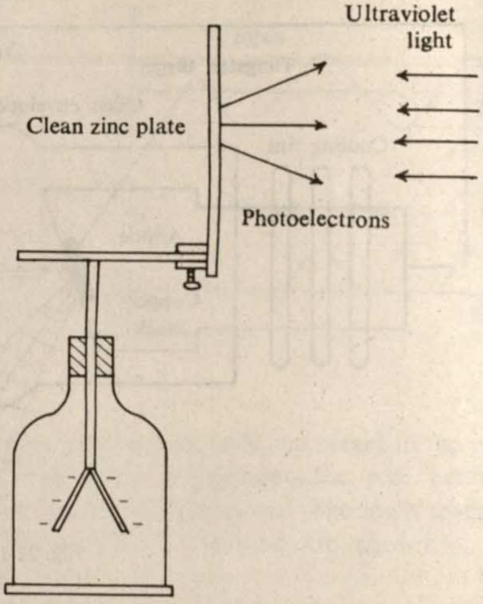


Fig. 22.13

The apparatus shown in Fig. 22.14 can be used to conduct experiments with lights of different frequency and intensity, using various metals. Light enters through the window into an evacuated envelop and is made to fall on the shiny metal surface of the emitter. Electrons are emitted from the metal surface. They travel to the positively charged plate, producing a current which deflects the needle of the galvanometer. If the intensity of light is increased, the current increases. Thus intensity controls the number of electrons emitted.

Now if the plate is made *negative* with respect to the emitter as shown in Fig. 22.14(b), the electrons get repelled and very few reach the plate. For a particular value of V, all the electrons are stopped. Increasing the intensity of light does not start the current. However, on

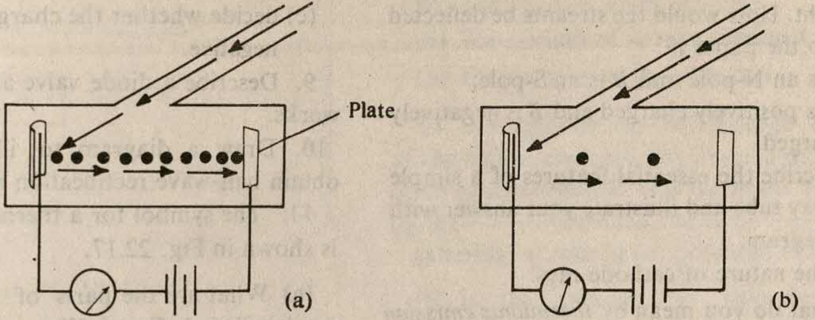


Fig. 22.14

changing the frequency of light, it is observed that at a particular frequency the current starts again. As frequency is increased further, the current increases showing thereby that when light of higher frequency is incident on the metal surface, electrons are emitted at higher speeds. For very low frequencies no electrons are emitted and there is no current even if the plate is positive.

From these observations we conclude that:

1. The intensity of light controls the number of electrons emitted per unit time from the metal surface.
2. The frequency of light controls the energy of the electrons emitted. If the frequency is very low, no electrons may be emitted.

Applications of Photoelectric Effect

The effect is put to use in **photocells** which have numerous applications in science and industry. They are used in burglar alarms, automatic devices for switching on lights at dusk, television cameras and for sound reproduction in cine sound projectors. In the latter, light is first allowed to pass through the sound track of the film. After passing through the track the intensity of light varies with the sound frequency. The light is then made to fall on caesium photocells. The current and hence the voltage produced by the photocell varies according to the intensity of light and hence according to the frequency of sound. This voltage is amplified and the output is fed to loudspeakers to reproduce the sound recorded in the sound track.

Photocells made from semiconductors such as silicon are used to convert solar energy into electrical energy. Satellites and space ships have large solar panels consisting of hundreds of such solar cells which provide the necessary electrical energy to operate the various instruments in them.

QUESTIONS

1. With the aid of a clear diagram describe the phenomenon of electric discharge through rarified gases.

2. What is an electron? How many electrons convey one coulomb and how does its mass compare with that of hydrogen?

3. The arrow in Fig. 22.15 represents a stream of electrons moving in the plane of paper from

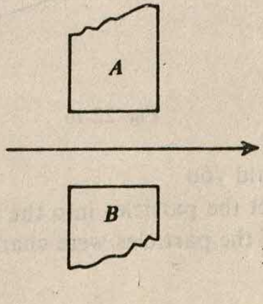


Fig. 22.15

left to right. How would the streams be deflected relative to the paper if

(a) A is an N-pole and B is an S-pole;

(b) A is positively charged and B is negatively charged.

4. Describe the essential features of a simple cathode ray tube and illustrate your answer with a clear diagram.

State the nature of cathode rays.

5. What do you mean by *thermionic emission* and *space charge*. How can you show experimentally the emission of electron from a hot cathode? What will you do to obtain an intense beam of electrons at comparatively low temperature?

6. Draw a labelled diagram to show the components of a hot cathode ray tube. Show electrical connections required to enable the tube to produce a fine beam of electrons.

What are the properties of cathode rays? State briefly with necessary diagrams how three of these properties can be demonstrated.

State two properties which may (erroneously) show that cathode rays might not be electrons but are electromagnetic waves.

7. Draw a labelled diagram of a cathode ray oscilloscope tube showing its essential parts. Explain how a C.R.O. is used to examine the variation with time of the p.d. between the terminals of an a.c. generator.

8. A cathode ray tube was modified by sealing a small metal can inside the glass envelope as shown in Fig. 22.16.

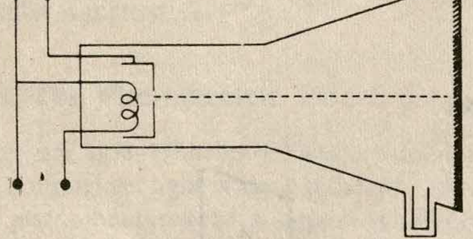


Fig. 22.16

How could you

(a) deflect the particles into the metal can;

(b) tell if the particles were charged;

(c) decide whether the charge was positive or negative.

9. Describe a diode valve and explain how it works.

10. Draw a diagram to illustrate how to obtain half-wave rectification using a diode.

11. The symbol for a thermionic diode valve is shown in Fig. 22.17.

(a) What are the parts of this valve which are labelled A, C and H?

(b) What is the function of H?

(c) What is the function of C?

(d) What is the function of A?

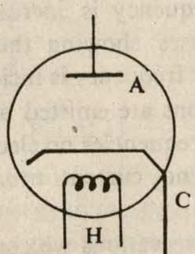


Fig. 22.17

12. In the circuit shown in Fig. 22.18 a reading was obtained in the milliammeter.

What would be the effect (if any) on the milliammeter reading when each of the following alterations was made in turn to the above circuit?

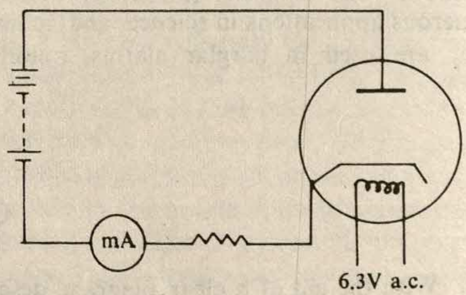


Fig. 22.18

(a) Reversing the resistor R.

(b) Disconnecting the 6.3 V a.c. supply.

(c) Reversing the battery.

13 (i) In Fig. 22.19 label the components A, B, C and D.

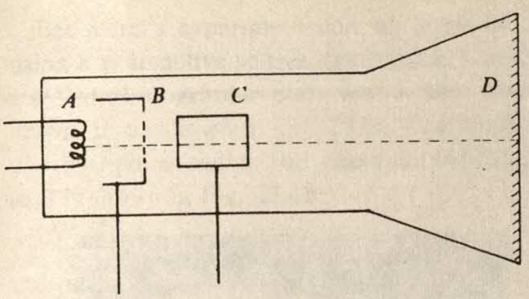


Fig. 22.19

(ii) State which is connected to the positive of a high tension supply.

(iii) What is the purpose of the coating *D*?

(iv) On the diagram, draw and label the parts which make it possible for electrostatic forces to deflect the electrons towards *E*.

14. Draw a labelled diagram of a *hot-cathode X-ray tube* together with a simplified circuit diagram to indicate the kind of electric power supply required to work it. Mention practical uses of X-rays.

State the factors which govern

(a) Wavelength of X-rays obtained.

(b) the intensity of the *radiation*.

15. In a cathode ray oscilloscope brightness of the spot is controlled by making the———— more or less negative, and the beam is focused by the————between the two————.

(altering, anodes, grid, potential difference)

16. In the cathode ray tube———— are emitted from the————accelerated by———— and strike the————screen making a bright spot of————.

(anode, cathode, light, flourescent, electrons)

17. State the principle of photoelectric emission. Describe an experiment to illustrate this effect and draw a neat labelled diagram of the apparatus used. Give three applications of the photoelectric effect. Explain one application in detail.

23

Radioactivity and Nuclear Energy

On July 16, 1945 the world's first atomic bomb was exploded in a remote desert plateau in New Mexico. A small piece of uranium, smaller than the size of a football had changed the history of the world. In 1954, the first nuclear powered submarine *Nautilus* was launched by the U.S.A. She travelled 60,000 miles or 96,000 km using only 4 kg of uranium fuel. To cover the same distance using diesel motors, the submarine would have used 16 million litres of oil. In 1956, the world's first nuclear power station was opened at Calder Hill in Cumberland. At a time when the Earth's supply of fossil fuel is gradually disappearing, fast breeder reactors will provide a source of almost limitless energy. The chance discovery of natural radioactivity by Professor Becquerel in 1896 was the first step towards the development of nuclear energy. This chapter is a history of the discoveries that led to nuclear powered ships, nuclear generators, nuclear weapons, cancer destroying nuclides, radioactive tracers and plasmas.

23.1 Discovery of Natural Radioactivity

Natural radioactivity was discovered by Professor Henery Becquerel after the discovery of X-rays by Professor Röntgen who had concluded that X-rays are produced from the spot where flourescence is caused by cathode rays in discharge tubes. Professor Becquerel and his father were interested in the flourescence of uranium salts. He thought that these might give off X-rays when they are exposed to sunlight.

To test his hypothesis, he wrapped a photographic plate in a black paper, placed a coin on it and then a crystal of uranium salt over the coin. He exposed the crystal to strong sunlight to make it glow and then developed the film. He was thrilled to find that the photographic film was darkened except for the part covered by the coin. He naturally thought that uranium must have emitted X-rays or some similar radiations.

Becquerel decided to repeat the experiment, but when he was about to do so clouds came and covered the sun. He put the photographic plate and the crystal into a drawer and waited for a sunny day. Several days passed but it remained cloudy. Tired of waiting, Becquerel decided to develop the plate without having the crystal exposed to sunlight. To his surprise the plate had been blackened as before! He repeated the experiment in complete darkness and obtained exactly the same result. Sunlight and flourescence had therefore nothing to do with the emission of this *radiation* from uranium salt. Unlike X-rays this radiation is emitted without any excitation. It 'just happened'. Becquerel had discovered what Madam Curie later called *radioactivity*.

We call this radiation a *radioactive radiation* and the source a *radioactive source*.

Becquerel's experiment can be repeated by using a radioactive source (radium) held above a sealed photographic plate with a key placed above it as shown in Fig. 23.1a. The resulting photograph showing the effect of radioactive rays is shown in Fig. 23.1b.

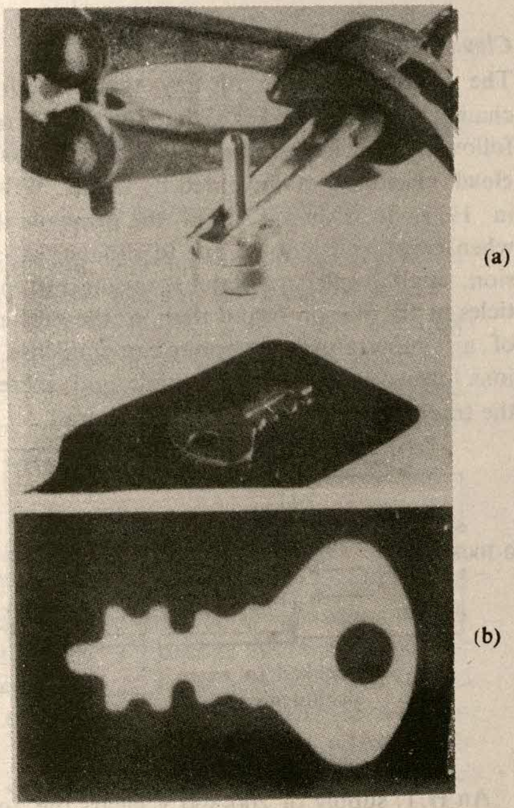


Fig. 23.1

A student of physics and chemistry, Marie Curie-Sklodowsky (1867-1934) was so fascinated by the phenomenon of 'Uranium rays' that she decided to write a thesis for her doctorate on this subject.

She found that the rays from uranium caused ionisation of air molecules and saw in this a means of measuring the intensity of the radiation. A simplified version of her apparatus is shown in Fig. 23.2.

It consists of two isolated metal plates fitted inside an earthed metal box called an *ionization chamber*. The lower plate is raised to a high potential by joining it to the positive pole of a battery and the upper plate is joined to the negative pole through the pulse electroscope. Radioactive material is spread on the lower plate.

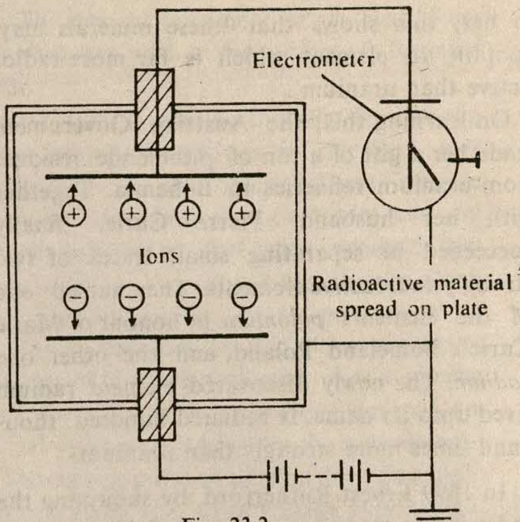


Fig. 23.2

Radiations emitted by the radioactive material ionize the air between the two plates by knocking off electrons from the atoms of the air. The free electrons may then attach themselves to other atoms to form negative ions. The ions flow towards respective electrodes as shown in Fig. 23.2 to produce a tiny ionizing current. The leaf gets charged up and deflects. As soon as it touches the side electrode it gets discharged and falls back. The process repeats again and again. The number of pulses produced per second is a measure of ionizing current which in turn depends upon the intensity of radiation.

Using this type of radiation detector Curie tried various chemicals and discovered that apart from the element uranium the only other element which emitted similar radiation was *thorium*. In all other elements the search for radioactivity was fruitless. However, she made one startling discovery. When she compared the radiation intensity from two compounds of uranium, *pithblende* and *chalcolite*, with that from pure uranium metal she found that pithblende and chalcolite were much more radiative than pure uranium. According to her, this shows that 'these minerals may contain an element which is far more radioactive than uranium'.

On learning this, the Austrian Government made her a gift of a ton of pithblende residues from uranium refineries in Bohemia. Together with her husband, Pierre Curie, finally succeeded in separating small traces of two strongly radioactive elements. They named one of the elements *polonium* in honour of Marie Curie's homeland Poland, and the other one *radium*. The newly discovered element radium lived upto its name. It radiated hundred thousand times more strongly than uranium.

In 1899 Ernest Rutherford, by subjecting the radiation to transverse magnetic field was able to show that a part of radioactive rays behaved like positively charged particles and another part as negatively charged particles. He named the positively charged particles as *alpha particles* and the negatively charged particles as *beta particles*. In 1900, Villard discovered a third constituent which was unaffected by magnetic field and behaved like electromagnetic waves. He named them *gamma rays*.

23.2 Methods of Detection

Radioactive radiations cause ionization in gases, cause flashes of light to be given off from certain substances, and affect photographic film. All these effects are used to detect radioactivity.

Scintillation Counter

Certain substances such as zinc sulphide emit flashes of light when radioactive particles strike them. These flashes of light are called *scintillations*. This effect can be observed in a dark room using the instrument as shown in Fig. 23.3.

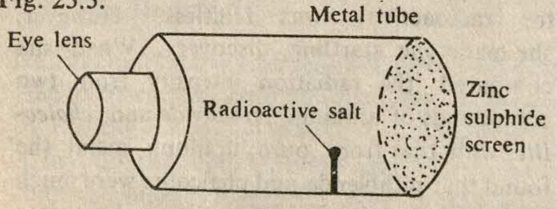


Fig. 23.3 Scintillator

Early experimentors used to sit in dark rooms for counting flashes of light. Nowadays photoelectric cell and a scaler are used alongwith a scintillator. For each flash of light the photoelectric cell produces a separate electric pulse which is counted by the scaler

Cloud Chamber

The great advantage of any type of cloud chamber is that it makes visible the actual track followed by a charged particle. The **expansion cloud chamber** was invented by C.T.R. Wilson in 1911. It is based upon the principle that when moist air is cooled due to sudden expansion, small droplets of water form on dust particles in air. Wilson found that in the absence of air supersaturated vapour can condense on ions formed by a charged particle and thereby the track becomes visible as a white trail.

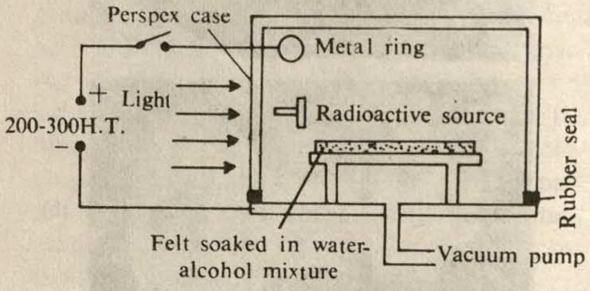


Fig. 23.4 Expansion cloud chamber

An H.T. supply of 200-300 V clears the ions already present. This ensures that when the handle of the pump is suddenly pulled out, the observer only sees the tracks of the charged particles which have just left the source.

The diffusion cloud chamber was designed by Langsdrof in 1939. It is an improvement on the expansion cloud chamber as it works continuously.

The floor of the chamber is closed using solid carbon dioxide (dry ice) of m.p. − 38°C. A felt ring at the top is soaked with alcohol and water mixture. Alcohol evaporates and cools as it diffuses down. Conditions are right for alcohol vapours to condense. However, the vapours can only condense on dust particles (which are not there) or ions. As the source

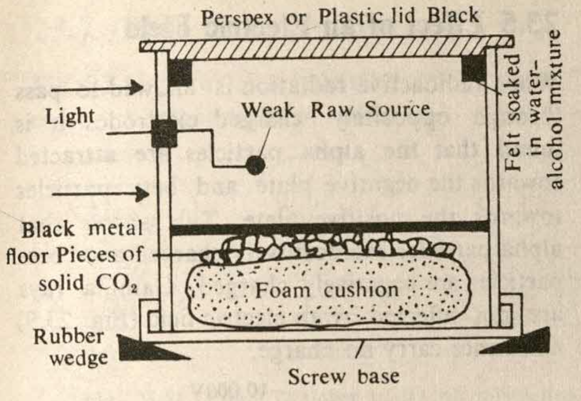

Perspex or Plastic lid Black
Light
Weak Raw Source
Felt soaked in water-alcohol mixture
Black metal floor Pieces of solid CO$_2$
Foam cushion
Rubber wedge
Screw base

Fig. 23.5 Diffusion cloud chamber

produces ions, vapours condense on them. The droplets reflect light and hence can be seen.

Note that what you are seeing is not the actual radiation but alcohol droplets which have formed on ions produced by the radiation. Rubbing of the perspex top with cloth electrifies it, which removes any unwanted ions.

Geiger Muller Tube

This was first designed by Geiger Muller in 1928. The commonly used tube consists of a metallic tube having a thin wire passing through its middle. The tube acts as a cathode and the wire as an anode. A p.d. of 350 to 450 V is applied across them through a high resistance as shown in Fig. 23.6. It has a thin mica window which allows charged particles or pulse radiations to enter. The tube contains neon or argon at 10 cm of Hg pressure and a few traces of bromine vapour.

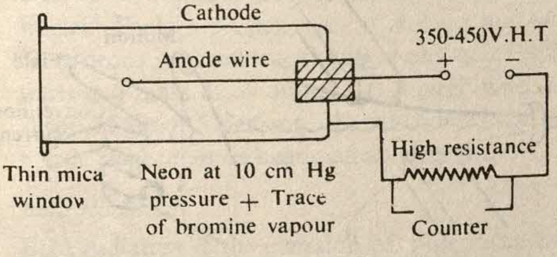


Fig. 23.6 Geiger Muller tube

A beta particle entering the tube through the window produces some ions in the gas as it collides with the gas atoms. These ions are attracted towards respective electrodes and get so much accelerated that they produce new ions on colliding with other gas molecules which in turn also get accelerated to produce more ions. The process goes on and ultimately many thousands of ions are produced. An *avalanche* of ions, therefore, strikes the electrodes and an electrical pulse travels between the two electrodes. The current pulse on passing through a high resistance gives rise to a voltage pulse which is registered on the scaler which gives the number of radiation pulses or particles entering the G.M. tube in a given time. The bromine vapour acts as a *quencher* to clear the tube of ions so that it is ready to receive the next particle.

A G.M. tube with a scaler will detect beta and gamma radiation. It can also detect alpha radiation provided the window is thin enough to allow it to enter the tube.

23.3 Absorption of Radiation

When radiation penetrates matter, it loses energy by collision with atoms and molecules of matter. Finally, it becomes so slow that it is unable to penetrate further and is said to have been **absorbed.** With the help of this property of absorption it can be demonstrated that there are three distinct types of radiation.

Activity 1. Take a radium source which emits all types of radiations. Place a Geiger tube connected to a rate-meter or a scaler as shown in Fig. 23.7. Insert a thin paper between the source and the detector. The count-rate is found

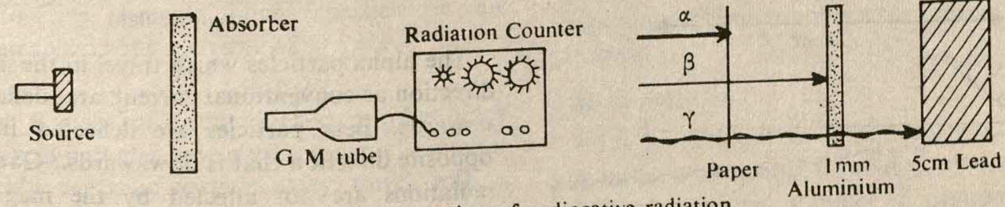


Fig. 23.7 Absorption of radiocative radiation

to fall showing that some type of radiation has been absorbed by the paper. The radiation absorbed by a thin paper is the **alpha radiation** (α-radiation) which is the least penetrative of all radiations. A source which emits only alpha radiation is called a pure *alpha source.* A suitable school laboratory α-radiation source is amercium-241 ($^{241}_{95}Am$).

Next insert a sheet of aluminium or a thick paper between the source and the detector. The count-rate is found to fall further. The extra radiation which has been absorbed by an aluminium sheet is the **beta-radiation** (β-radiation). A pure beta source is strontium-90($^{90}_{38}Sr$).

When a thick sheet of lead is inserted between the source and the detector the reading drops even further. This indicates that there is a third type of radiation which is stopped by a thick lead sheet. This is the **gamma radiation** (γ-radiation). Cobalt-60($^{60}_{27}Co$) is a pure γ-source.

Even on inserting a thick lead sheet, the count-rate does not become zero. This is because of the **background radiation**, which is the radiation which exists even when all radioactive radiation has been absorbed. Background radiation is present all the time and originates from outer space and from natural radioactivity around us.

23.4 Range in Air

Alpha and beta particles are slowed down and stopped by collisions with air molecules. The distance covered by a radiation in air before it is absorbed is called its *range in air.* Gamma rays are hardly affected by the air. Only their intensity gets less as they spread out. It becomes 1/4 when the distance between source and detector is doubled and becomes 1/9 as distance becomes three times., i.e. Intensity $\propto 1/(\text{distance})^2$.

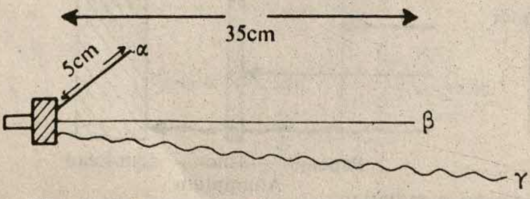


Fig. 23.8 Range of radioactive radiation in air

23.5 Effect of an Electric Field

When radioactive radiation is allowed to pass through oppositely charged electrodes it is found that the alpha particles are attracted towards the negative plate and beta particles towards the positive plate. This shows that alpha particles are positively charged and beta particles are negatively charged. Gamma rays are not affected by an electric field (Fig. 23.9) and hence carry no charge.

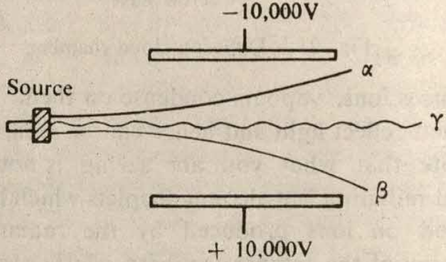


Fig. 23.9 Deflection of radioactive radiation by electric field

23.6 Deflection by a Magnetic Field

On applying a transverse magnetic field to the radiation, the alpha and beta particles are deflected in a direction which is at right angles to the magnetic field and the direction of their travel. The deflection is according to Fleming's left-hand rule as is shown in Fig. 23.10.

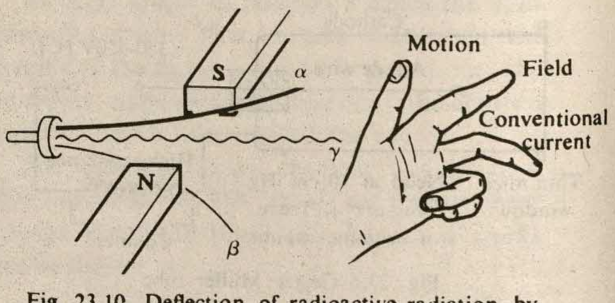
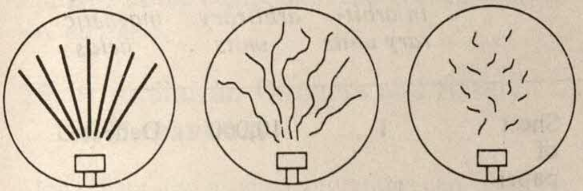


Fig. 23.10 Deflection of radioactive radiation by magnetic field

The alpha particles which travel in the same direction as conventional current are deflected upwards. Beta particles are deflected in the opposite direction that is downwards. Gamma radiations are not affected by the magnetic field and keep moving in the same direction.

23.7 Cloud Chamber Tracks

Fig. 23.11 shows cloud chamber tracks produced by the three types of radiation.



α particles β particles γ rays

Fig. 23.11 Cloud chamber tracks of radioactive radiation

Tracks of alpha particles are thick because they are good ionizers and straight because they are comparatively heavy and are not easily deflected from their path on colliding with air molecules.

β-particle tracks are thin and wavy because they are poor ionizers and being light are easily deflected from their path by collisions with air molecules.

γ-rays are very poor ionizers. The faint wavy trails are caused by electrons knocked off from air molecules when they are struck by γ-rays.

23.8 Nature of α, β and γ Radiations

Alpha Radiation

Alpha radiation is the emission of alpha particles in a random way from the radioactive nuclei. Each α-particle is a *helium nucleus* (2 protons + 2 neutrons) with a charge of +2 units and mass of 4 units. It travels with a speed of about 5 percent of that of light and is about 8000 times as heavy as an electron.

Beta Radiation

Beta radiation is the emission of β-particles in a random way from the unstable nuclei of radioactive elements. Each β-particle is an electron carrying a charge of

$$e = -1.6 \times 10^{-19}\mathrm{C}$$

and a mass of about 1/1840 of a hydrogen atom. β-particles have a wide range of energies; highly energetic particles may travel with a speed approaching that of light, for example around 2.5×10^8 m/s. As a β-particle has a very small mass and is a fast moving charged particle, it is strongly deflected by a magnetic and an electric field.

Gamma Radiation

These are not particles but electromagnetic waves similar to X-rays but having shorter wavelengths of the order of 10^{-11} metres. The actual wavelength depends on the radioactive substance emitting them. Like other electromagnetic radiations, they travel with a speed of 3×10^8 m/s.

The properties of alpha, beta and gamma radiations are summarised in Table 23.1.

23.9 Nuclear Reactions

You know that an atom consists of a small positive charged **nucleus** containing neutrons and protons with negatively charged **electrons** revolving round the nucleus.

The total number of protons and neutrons in the nucleus of an atom is called its **mass number** *A*. Thus, mass number of an atom is equal to the number of nuclear particles or *nucleons*. The number of protons in the nucleus of an atom is its **atomic number** *Z*. It is, therefore, equal to the number of positive charges in the nucleus. For example, the mass number A of helium is 4 and atomic number Z is 2. It is therefore represented as ${}^{4}_{2}\mathrm{He}$ or sometimes as ${}^{4}\mathrm{He}_2$.

Radioactivity occurs as a result of the instability of the nucleus. With the emission of radiation from the nucleus, its structure changes and it becomes more stable. If an alpha or beta particle is emitted, the atomic number of the element changes and a new element called the *daughter product* is formed. This daughter product may itself be unstable and may emit radiations. This continues till a stable atom is formed.

Alpha Emission

When a nucleus ejects an α-particle, its mass or nucleon number A is reduced by 4 and the proton or atomic number Z decreases by 2.

Table 23.1

Name	*Nature*	*Mass (proton = 1)*	*Charge (proton = + 1)*	*Speed*	*Stopped by*	*Penetration power in arbitrary units*	*Ionizing power in arbitrary units*	*Effect of electric or magnetic fields*
Alpha particle	Helium nuclei $^{4}_{2}He$	4	+2	5% of the speed of light	Sheet of paper	1	10,000	Deflected
Beta particle	Electron $_{-1}^{0}e$	$\frac{1}{1840}$	−1	90% of the speed of light	1-2 mm thick aluminium sheet	100	100	Deflected strongly
Gamma rays	Bursts of electro-magnetic radiations of very short wavelength	zero	zero	Speed of light equal to 3×10^8 m/s	Many centimetres of thick lead sheet	10,000	1	Not deflected

For example

$$^{A}_{Z}X \longrightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He$$

or

$$^{232}_{90}Th \longrightarrow {}^{228}_{88}Ra + {}^{4}_{2}He$$

This process is called *radioactive transmutation*.

Beta Emission

When a nucleus ejects a β-particle, one of its neutrons changes to a proton. Hence, mass or nucleon number remains the same and the atomic or proton number increases by 1. For example,

$$^{A}_{Z}X \longrightarrow {}^{A}_{Z+1}Y + {}_{-1}^{0}e$$

$$^{228}_{88}Ra \longrightarrow {}^{228}_{89}Ac + {}_{-1}^{0}e$$

Gamma Emission

Often a daughter nucleus is left in an excited state and the rearrangement of nucleons takes place in about a microsecond. This results in the release of high energy electromagnetic radiation called γ-rays. Mass and atomic number remains unchanged.

Nuclides

Whenever we specify a particular *A* and *Z* for an element we refer to it as a *nuclide* and if the nuclide is unstable it is called a *radionuclide*.

If one nuclide has the same proton number (*Z*) as another but different mass numbers, they are called *isotopes* of that element. They occupy the same place in the periodic table (*isos*-same, *topos*-place). For example $^{228}_{88}Ra$ and $^{234}_{88}Ra$ are the isotopes of radium and have the same chemical properties.

If a radioactive nuclide emits one α-particle and two β-particles we get an isotope of the same element. For example,

$$^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He$$

$$^{234}_{90}Th \rightarrow {}^{234}_{91}Pa + {}_{-1}^{0}e$$

$$^{234}_{91}Pa \rightarrow {}^{234}_{92}U + {}_{-1}^{0}e$$

The rate at which a radioactive nucleus disintegrates is entirely independent of any physical and chemical change to which the substance may be subjected, e.g. temperature, pressure and type of the compound the element forms has no effect.

23.10 Radiation Dangers and Safety Precautions

Alpha, beta and gamma radiations can destroy living cells by producing ionization in their molecules. Relatively short exposure to intense radiation can cause radiation sickness, blisters and sores slow to heal, and, in several cases, death. Long-term exposure to weaker radiation can eventually cause cancer, leukemia, eye cataracts and hereditary defects. The most readily affected parts of the body seem to be the reproductive organs and kidneys. These dangers are aggravated by the fact that

(i) different sources remain active for different lengths of time, and
(ii) certain radioactive elements are taken up by specific organs.

Alpha sources are very dangerous if swallowed or inhaled (when the source is gaseous such as Rn—220) as they are highly ionizing. However, these are relatively safe outside the body as the radiation can be stopped even by a paper and their range in air is only 4-8 cm. Beta particles are more penetrating but outside the human body they do not pose safety hazards as they can be stopped by a few millimetres thick aluminium sheet.

Though gamma radiations are the least ionizing, they are the most dangerous as they can penetrate deep into the body. In research establishments protection is achieved by (1) screens of several centimetres of lead or several metres of concrete (2) handling of sources by remote control.

Great care needs to be taken to handle plutonium-239 which is obtained as a by-product in breeder reactors and is itself an important fuel used in reactors and atomic bombs. Its half-life is 25,000 years, and so it would remain active for a very long time if there was an accident involving it. This poses difficult problems in its transportation and disposal.

23.11 Applications of Radioactivity

1. *Production of Radioactive Nuclides*

Alpha particles were used as missiles by early scientists for bombarding elements to produce radioactive nuclides. In 1935 Juliot-Curies received the Nobel Prize in chemistry for producing the first artificial radio nuclide (radio isotope) by the bombardment of aluminium with α-particles.

$$^{27}_{13}\text{Al} + ^{4}_{2}\text{He} \rightarrow ^{30}_{15}\text{P} + ^{1}_{0}\text{n}$$

$^{30}_{15}\text{P}$ itself is radioactive. On disintegration it emits positron (or positive β-particle) and an isotope of silicon

$$^{30}_{15}\text{P} \rightarrow ^{30}_{14}\text{Si} + ^{0}_{+1}\text{e}$$

During the last 50 years more and more nuclides have been produced; at present more than 1500 are known. cobalt-60 is an important nuclide which alone is now put to more than 100 uses. It is produced by the bombardment of cobalt-59 atoms with neutrons.

$$^{59}_{27}\text{Co} + ^{1}_{0}\text{n} \rightarrow ^{60}_{27}\text{Co}$$

It emits γ-radiations and is used for destroying cancerous growths or tumours.

2. *Tracers*

Use of radio nuclides as tracers is based upon the fact that they are easily *detectable*. They are added in extremely small amounts to the area to be studied. For example, in order to treat thrombosis (blood clots), it is essential to know the position of blood clot in the body. Radioactive sodium is added to the body and using detectors (like G.M. counter) it can be found where the flow of blood stops. Another use of tracer in *medicine* is to find the uptake of certain elements by the organs of the body. For example, the function of thyroid gland which normally takes up iodine that enters the body can be investigated by injecting radioactive iodine.

Radioactive phosphorous is added to fertilizers and food to study the uptake of certain elements by plants and animals. The first recorded use of a *tracer* is as follows. Professor George Von Hevesy was staying in a boarding house in which he suspected that the stew was made sometimes from scraps left over from earlier meals. One day he added a little radioactive lead to the food left on his plate. When food was served next day to him he took a sample of it and tested it for radioactivity. The Professor's fears were confirmed.

To make the dredging of canals and harbours more efficient radioactive silicon is added to the mud to know how the mud moves and builds up.

3. *Medicinal Uses*

The γ-rays emitted by Cobalt-60 destroy living tissues and are used to kill malignant cancer cells in the human body. If the cancer is right inside the body, a beam of γ-rays of lethal intensity for tumour will also damage other parts of the body through which they pass. This is avoided by making the cobalt source rotate in a circle in such a way that the beam of γ-rays that it produces is always directed towards the centre where the tumour is located, Fig. 23.12.

As the source rotates, the radiation dose is very great at the centre while surrounding healthy cells only receive radiation for a short while, and, therefore, are not damaged.

The radiation picture in Fig. 23.13 was constructed from seven 'scans' of a human body. The spots indicate the presence of radioactive atoms. The bright cluster in the lung region indicates an abnormal condition. Radioactive scanning of this kind often reaches areas which X-rays cannot reach.

As radioactive rays kill bacteria, hypodermic needles, dressing and syringes can be *sterilised* without boiling after they have been packed in airtight polythene containers by exposing them to radioactive rays. Tinned foods are found to keep fresh longer after such irradiation.

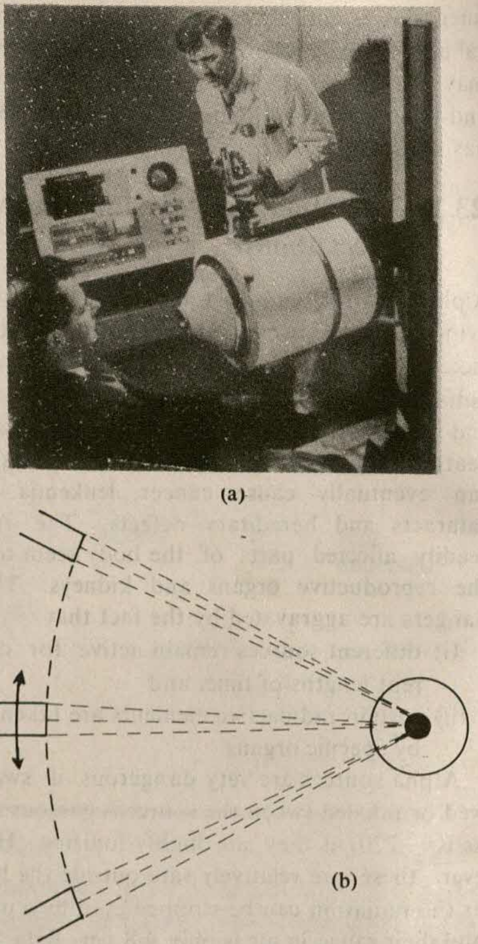


Fig. 23.12 Treatment of cancer by γ-rays

4. *Industry*

Radioactive nuclides are used in industry to detect flaws, to measure thickness of materials, to remove unwanted static electricity and to control quality. To test, for example, a tyre cord using radioactive material, a strontium-90 source is placed on one side of the tyre cord with a detector on the other side. If the tyre cord is thin, the detector will give a higher count rate. Similar apparatus can be used to reject an article of wrong dimensions.

Radioactive plutonium was chosen to power the electronic equipment in the American navigational satellite launched in 1961. Strontium-90 is used in the 5 watt RIPPLE generator

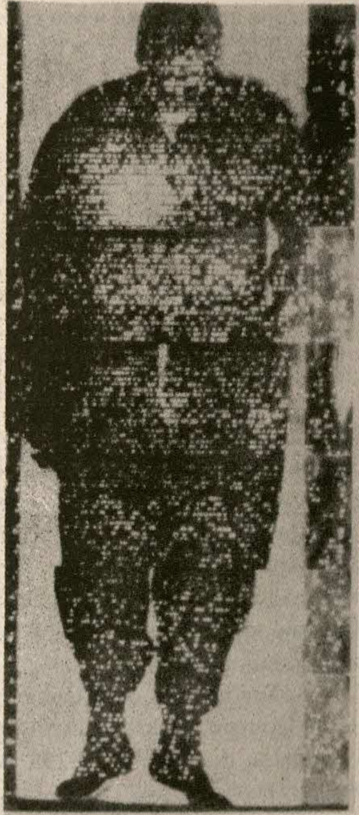


Fig. 23.13 Radiation scan of human body

(radio isotope powered prolonged life equipment) which can operate for 5 years without refuelling. It can be used in unmanned weather stations, repeater stations and satellites. Atomic Energy Commission of America has developed a 'heart pacemaker' powered by plutonium-238 which only weighs 300 g and operates without attention for 5 years. It contains electronic circuits requiring 50 microwatts to deliver small electric shocks to the heart 70 times a minute.

5. *Agriculture*

Seeds exposed to radioactive rays can germinate and grow into plants with unusual and often improved characteristics. For example, exposure of oats to radiation has led to the development of a new strain of oats which is practically resistant to disease.

Radiations are used to sterilize insects. Screw-worm flies were a great nuisance on the island of Curacao. Many male flies were bred and sterlized. The female screw-worm flies only mate once. When sterilized males were let loose on the fly population, the numbers were subsequently reduced. This process was repeated until this insect pest was completely eliminated.

6. *Carbon Dating*

Cosmic ray neutrons react with atoms of nitrogen present in the atmosphere to produce the radio nuclide carbon-14

$$^{14}_{7}N + ^{1}_{0}n \rightarrow ^{14}_{6}C + ^{1}_{1}H$$

Living plants absorb carbon dioxide from the atmosphere. Most of this carbon dioxide contains the common stable isotope carbon-12 ($^{12}_{6}C$) but some of it contains radioactive isotope carbon-14 ($^{14}_{6}C$). We assume that the proportion of carbon-14 to carbon-12 in the atmosphere is constant and the proportion contained by the living plants is the same. However, when the plant dies the carbon-14 decays with a half-life of 5600 years emitting β-particles. Hence with time the proportion of C-14 to C-12 in the plant decreases. By measuring this proportion, it is possible to estimate how long ago the plant or its wood was living. This method is called carbon dating and has been used in estimating the age of wood in Egyptian tombs and ancient papyrus manuscripts.

The age of certain rocks has been estimated by assuming that the uranium-238 present in them was formed at the same time as the rock itself. As uranium-238 decays with a half-life of 4500 million years and actually turns to lead, the relative quantities of uranium and lead present in a sample of rock enables us to tell its age.

23.12 Nuclear Fission and Energy

In 1934, Juliot-Curies discovered artificial radioactivity by bombarding light elements with α-particles, and in the same year Fermi in Italy and Lawrence in America obtained radio isotopes by bombarding stable elements with accelerated protons. In the reaction

$$^{7}_{3}Li + ^{1}_{1}H + 0.5\ Mev \rightarrow ^{4}_{2}He + ^{4}_{2}He + Mev$$

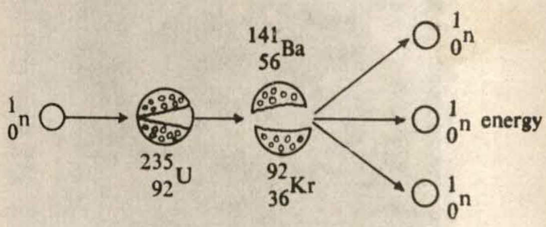
The energy of α-particles was found to be very much greater than the energy of protons. Where did this extra energy come from? It was also found that the total mass of reactants is greater than the total mass of products. This loss of mass is converted to energy according to the famous Einstein equation $E = mc^2$.

In atomic physics energy is measured in *electron volts.* When an electron or proton is accelerated by a difference of potential of 1 volt, the energy gained by it is 1 eV.

$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ Joules}$$
$$1 \text{ MeV} = 1.6 \times 10^{-13} \text{ Joules}$$

Accelerated protons and α-particles are not good missiles for bombarding nuclei as they are repelled by the positively charged nuclei and a large energy has consequently to be imparted to them for bombardment. As neutrons carry no charge, they are not repelled and slow-moving neutrons are consequently very useful for bombardment. Fermi observed that when the neutron source and target were placed on a wooden table the disintegration rate increased. He explained this by suggesting that neutrons become slow on colliding with hydrogen atoms in the wood. Slow neutrons spend a larger time in the proximity of the nucleus while fast neutrons fly past it with high speed. Thus, the probability of the capture of slow neutrons by attractive nuclear forces is considerably increased.

Four years later in 1938, two German scientists Otto Hahn and Fritz Strassmann bombarded uranium with neutrons. The uranium nucleus absorbed neutrons and then broke up into two other nuclei. One of the by-products was found to be barium of atomic number 56. Meitner and Frisch explained the reaction and guessed that the other element should be krypton-36. They concluded that a large amount of energy along with neutrons should be released when an atom of uranium is split into two middle-sized atoms. Here, for the first time in the great nuclide hunt, a bullet (neutron) caused a reaction releasing a large amount of energy and produced more bullets. On the average, two to three neutrons are released when one uranium nucleus splits (Fig. 23.14).



$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + ^{1}_{0}n + ^{1}_{0}n + ^{1}_{0}n$$

Fig. 23.14

Frisch and Meitner did not know what isotope of uranium had split and what isotopes of Kr and Ba were produced. The process was labelled *fission*, a name borrowed from a biologist's description of cell division.

Fermi's associates found that about 200 MeV energy is produced for each fission. Naturally occuring uranium contains 99.3% U-238 and 0.7% U-235. The nucleus of $^{235}_{92}U$ is much easier to split and later on it was realised that Hahn and Strassmann had split U-235 with slow neutrons.

This process of splitting up of U-235 nucleus into two smaller parts plus three more neutrons and a lot of energy is called **nuclear fission.**

The total mass of the fission products is less than the mass of the U-235 atom plus the neutron and this loss of mass is converted into energy in accordance with the Einstein equation:

$$E = mc^2$$

Each time a uranium nucleus splits, it releases three neutrons. These three neutrons may cause three further nuclei to split—the total of nine neutrons from them may cause nine more atoms to split up to produce twenty-seven neutrons and so on. This results in a **chain reaction** with vast amounts of energy being released (Fig. 23.15).

23.13 The Atom Bomb

By 1942 World War II was in its third year and most of the world's leading physicists were in

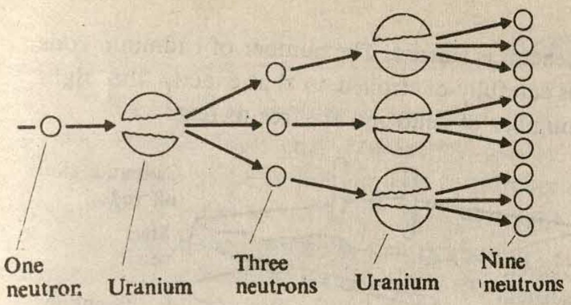


Fig. 23.15 Chain reaction

America. One group working under Enrico Fermi was working day and night to develop a nuclear reactor and another group led by Rober Oppenheimer was furiously trying to produce the first atomic bomb.

For the atomic bomb, pure U-235 was needed. Only 0.7% of U-235 is present in natural uranium. U-235 and U-238 are chemically identical, so they could not be separated chemically. Natural uranium was vapourized and allowed to pass through a very fine sieve, the lighter U-235 passing through more easily than the heavier U-238. This diffusion process was repeated thousands of times to obtain reasonably pure U-235. 80,000 people were employed and the output was only a few kilograms of uranium per week.

$^{235}_{92}$U readily accepts fast neutrons. In a small chunk of U-235, a chain reaction will not take place, as most of the neutrons produced escape through the surface.

Consider a sphere of U-235 of radius 2 cm. The ratio of the surface area to the volume is

$$\frac{4\pi r^2}{(4/3)\pi r^3} = \frac{4\pi \times 4}{(4/3)\pi \times 8} = \frac{3}{2} = 1.5$$

If the radius is doubled, the ratio becomes

$$\frac{4\pi \times 16}{(4/3)\pi \times 64} = \frac{3}{4} = 0.75$$

As the volume and thereby the mass of uranium is increased, the surface area per unit volume decreases and hence the chance of neutrons escaping the surface becomes less. In other words, on increasing the mass, the chance of neutrons produced to cause further fission increases. Eventually a stage could reach when a chain reaction may take place. The mass of uranium-235 needed to produce a chain reaction by the neutrons from the atmosphere is called *critical mass*.

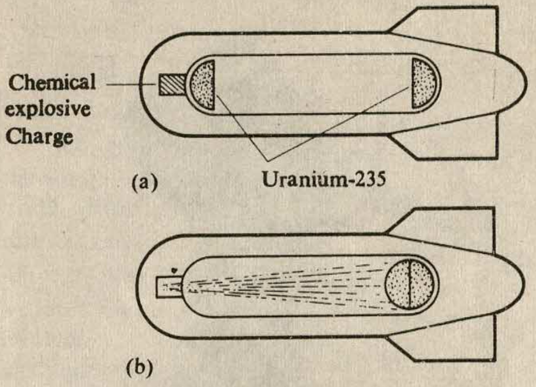


Fig. 23.16 The atomic bomb

The structure of a simple nuclear bomb is shown in Fig. 23.16a Two hemispheres of uranium-235, each of 3/4 of the critical mass are kept apart in a strong metal container. When the chemical charge is exploded, one hemisphere is violently forced against the other as shown in Fig. 23.16b making one sphere of 1½ times the critical mass.

There are always a number of neutrons flying around. Several hundred pass through our body every second. As soon as the mass of U-235 in the bomb exceeds the critical mass, the chain reaction is set up and the energy released results in a violent explosion (Fig. 23.17).

This can cause great devastation as it is many times more powerful than chemical explosives and radiation health hazards linger on as an after-effect. On July 16, 1945, the world's first atom bomb was exploded in New Mexico. It had changed the history of the world. India tested its first nuclear device underground at Pokharan on May 16, 1974.

23.14 The Nuclear Reactor

In a nuclear reactor the chain reaction is so adjusted that on the average, one neutron per fission splits another nucleus. The steady or controlled chain reaction is shown in Fig. 23.18.

Fig. 23.17 An atomic bomb explodes

A slow neutron is first captured by a U-235 nucleus, which then splits to form two nuclides which fly apart. The three fast neutrons produced by the fission are then made to pass through a graphite moderator in which they collide many times with carbon atoms and are slowed down and absorbed by cadmium rods. By gradually removing the cadmium rods, the reactor is started. The number of cadmium rods is carefully controlled so that exactly the right number of neutrons are free to react.

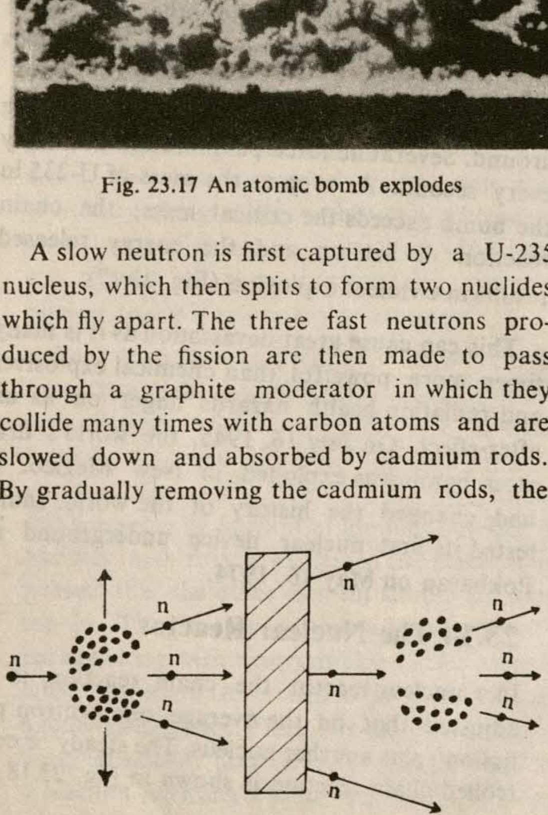


Fig. 23.18 Controlled nuclear reaction

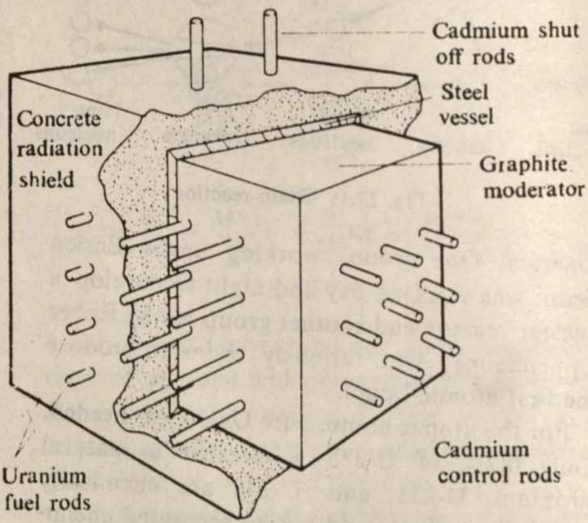


Fig. 23.19 Core of nuclear reactor

A bank of cadmium rods is kept ready to be introduced into the reactor to quickly shut it off at a time of emergency. Fig. 23.19 shows the core of a nuclear reactor.

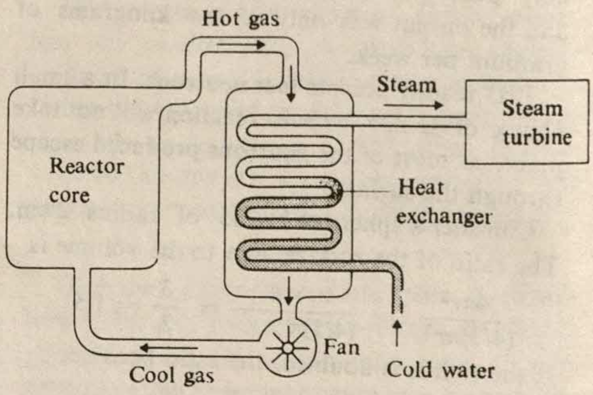


Fig. 23.20

The fission reaction produces heat energy. In the nuclear power station, the reactor core replaces the coal or oil fired boiler. Fig. 23.20 shows how the heat produced in the reactor is used to boil water. The steam produced drives a steam turbine which in turn drives the electrical generator.

QUESTIONS

1. Becquerel's experiment is repeated using a photographic film and radioactive source. Should an α, β or γ source be used to produce a shadow of a key on the resulting photograph? Explain your answer. Name one particular source that you would use to emit the specific radiation.

2. Explain whether α, β or γ radiations can be deflected by a magnetic field. Describe an experiment which verifies that one of these radiations can be deflected by a magnetic field.

3. Describe an experiment you would use to demonstrate that radioactive radiations are of three types.

4. Draw a labelled diagram of a G.M. tube. Explain how it is used to detect β-particles. Describe its action.

5. What do you mean by the range of α-particles? Name a detector which is used to detect them. Draw its labelled diagram and explain its action.

6. Give five properties each of α and β particles and γ-rays. Describe the nature of α and β particles and γ-radiations.

7. What is meant by radioactive decay, activity and half-life.

8. A radioactive element has a half-life of 2 days. If you start with 20 g, after 6 days how much of it will be left? What happens to the remaining mass?

9. A radioactive isotope has a half-life of 600 years. If original activity is 36 UCi, how long will it take for the activity to fall to 4.5 UCi?

10. An isotope of radon is represented by $^{222}_{86}\text{Rn}$.

(i) State how many protons and neutrons are contained in a nucleus of this isotope.

(ii) If this isotope decays with the emission of an alpha particle, find the new atomic number and mass number of the daughter product.

11. The isotope of actinium-226, $^{226}_{89}\text{Ac}$ decays by the emission of a beta particle. Find the atomic and mass number of the daughter product.

12. The following represents part of the decay chain for thorium:

$$^{232}_{90}\text{Th} \rightarrow {}^{228}_{88}\text{Ra} \rightarrow {}^{228}_{89}\text{Ac} \rightarrow {}^{228}_{90}\text{Th} \rightarrow {}^{224}_{88}\text{Ra}$$

State what particles are emitted at each stage of the chain. Which are the two isotopes and isobars?

13. What do you mean by an isotope? How can a radioactive element produce its isotope? Give nuclear equations of the change.

14. Identify the following radiations (not all of which come from radioactive sources) from the evidence supplied.

Radiation A: absorbed by a few centimetres of air; deflected by a magnetic field.

Radiation B: very penetrating rays; not deflected by a magnetic field, harmful to living organs.

Radiation C: mostly absorbed by a few millimetres of aluminium; deflected by a magnetic field.

Radiation D: has a wavelength of several metres; an aerial is required for the transmission of these waves.

Radiation E: can be detected by certain photographic plates and a thermometer with a blackened bulb; not visible to the human eye.

Radiation F: appears yellow to the naked eye; not deflected by a magnetic field; absorbed by black paper.

15. When a scientist in a nuclear power station examined some sea water which had become radioactive, he found that the emission of beta particles and gamma rays was due to a radioactive isotope which had a half-life of 15 hours.

(a) In the above statement:

(i) what are beta particles;

(ii) what are gamma rays;

(iii) what is meant by half-life of 15 hours.

(b) Why did the count rate decrease when he placed a 1 cm thick aluminium sheet between the sea water and the detecting instrument?

16. Explain why α-radiation from an α-source is likely to be less harmful to the internal

body organs than β and γ-radiation. What safety precautions are observed in handling radioactive sources.

17. (i) Describe how a cloud chamber works and what the tracks in Fig. 23.21 are.

(ii) State the kinds of particles which are causing the tracks in *A* and *B*.

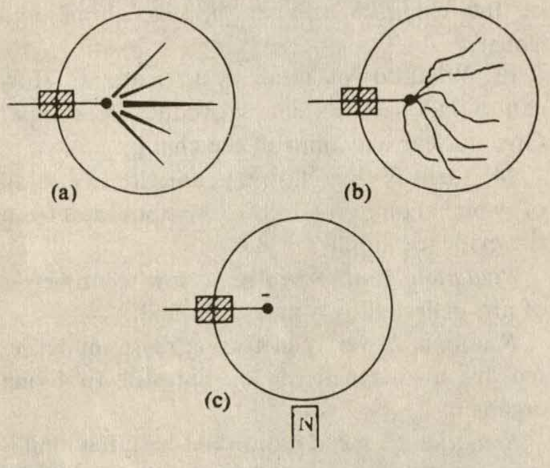


Fig. 23.21

(iii) What might you expect to observe if a piece of paper were placed in front of the source in each case and a magnet were held alongside the chamber as shown in Fig. 23.21c.

18. Explain what is meant by radioactive tracer and discuss their applications in industry, medicine and agriculture.

19. Describe briefly how a γ-radiation can be used in the fight against cancer.

20. Describe how an ancient wood bowl from an archeological site could be dated using a carbon dating technique.

21. (i) What is a neutron?

(ii) Why is it particularly valuable for bombarding atomic nuclei?

(iii) Why is energy released when a U-235 nucleus breaks up into two smaller nuclei?

(iv) What is the name given to this break-up?

(v) What is meant by a chain reaction, and why is a critical mass necessary to sustain one?

22. Discuss briefly the fission of uranium and how it can be controlled productively in a nuclear reactor.

24

The Universe and the Solar System

24.1 Expanding Universe

Astronomical observations have revealed that the universe is expanding outwards in all directions. This has led scientists to believe that the universe initially consisted simply of a black void with a single titanic blob of matter. Some twenty thousand million years ago a gigantic cosmic explosion took place sending out fragments of matter in all directions. These fragments, or heavenly bodies as we now know them, are still moving outwards. This theory is referred to as the **Big Bang Theory**. We thus live in a universe which is expanding just like a balloon being blown up.

24.2 Planets, Stars and Galaxies

Men have gazed in wonder at the heavens from very early times. In the morning you see the blazing Sun rising from the east like a fire ball which sweeps up in an arc to the highest point at noon and then goes down to finally set in the western horizon. On a clear night you see the sky studded with innumerable twinkling specks of light. We commonly call them 'fixed stars' or simply **stars** to distinguish them from the 'moving stars' which wander about in the sky. The latter are called the wanderers or **planets. Stars** *are luminous heavenly bodies which remain at definite places in the sky relative to other stars.* The Sun is a star. It is the star closest to the Earth. A **planet** *is a heavenly body which revolves round the Sun and is not luminous. Light from the Sun falls on it and is reflected to us.* The Earth on which we live is a planet.

With the naked eye, on a clear night, you can see about 6000 stars. If you use a small telescope you can see 100,000 stars. Through the most powerful telescope installed at Mt. Palomer Observatory in U.S.A., having a diameter of 5 m (200 inches), nearly twenty thousand million stars are visible. In our country the Nizamiah Observatory at Hyderabad has a 1.2 m (48 inches) diameter telescope.

The Light Year

Although stars appear to be tiny pinpoints of light to the naked eye, they are in fact very large celestial bodies that give out enormous amounts of light and heat. They seem so small to us because they are billions of kilometres away. Astronomers do not measure the celestial distances in kilometres but in **light years.** We know that light travels with a speed of 300,000 km/s. So in one year it will travel through a distance of $300{,}000 \times 365 \times 24 \times 3600 \simeq 9.5 \times 10^{12}$ km. Thus *one* **light year** *is the distance covered by light in one year and is approximately equal to* 9.5×10^{12} *km. It is used as a unit for measuring celestial distances.* The Sun is 8 light minutes (distance travelled by light in one minute) away from the Earth and the nearest star to the Sun, Proxima Centauri, is 4.3 light years from the Sun.

Galaxies

Although stars are very far apart, they appear to be grouped in clusters. Each family of star clusters is called a **galaxy**. *Thus a* **galaxy** *is a very large group of stars containing thousands of millions of stars.* They are of different sizes and shapes. The solar system is a part of a galaxy called the **Milky Way**. The Sun is only one of the innumerable millions of stars that make up our galaxy. The Milky Way has a spiral shape with the solar system being in one of the arms of the spiral (Fig. 24.1). A part of the galaxy can sometimes be seen as a faint band of stars stretching across the sky approximately in the north-south direction.

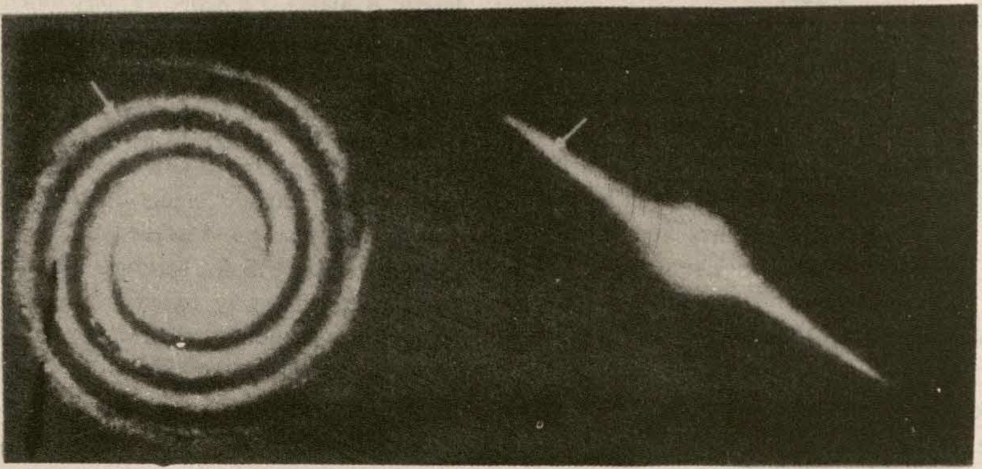


Fig. 24.1 The Milky Way. The arrows show the position of our solar system

The Milky Way looks like a poached egg hanging in space. Its diameter is about 150,000 light years and thickness is about 20,000 light years. The Sun is situated at a distance of 30,000 light years from its galactic centre. The Sun revolves around the galactic centre once in 250 million years, which is known as one **cosmic year**. The age of the Earth is about 3500 to 4000 million years. We can therefore say that the Earth is only 14 to 16 cosmic years old!

The Andromeda: On looking through a telescope beyond the Milky Way we find alternately dark spaces known as voids, stretching over thousands of light years, and clusters of several thousand stars forming other galaxies. The nearest galaxy is the Andromeda, 80,000 light years away. It is visible to the naked eye and can be distinguished as a faint blur against a clear moonless night sky. Thus you can claim that with a naked eye you can see as far as 80,000 light years!

There are several galaxies beyond Andromeda. With the help of an optical or radio telescope you can see stellar bodies as far as 10^{10} light years away. This means that the light that we receive now from these stars actually started 10^{10} years ago. In other words we can say that when we look out in space we are actually looking back in time!

In the empty space between galaxies large clouds of gas and dust, called **nebulae** are present. The galaxies, nebulae and empty space between them form the universe.

24.3 Constellations

On a clear moonless night we see numerous stars scattered all over in the sky. Most of them appear to form small groups having constant patterns. Such groups are called **constellations** and we identify them by their shape. Ancient Hindu and Greek observers imagined that each group had the form of an animal or a human being and they named each group according to their fancies. *A small group of stars having an unchangeable definite shape is called a* **constellation**. The position of each member of a constellation is fixed relative to the other members, and therefore their shape remains the same. Due to the Earth's rotation the constellations appear to move across the sky once every day. Also because of the Earth's rotation round the Sun, the position of the constellations keep changing during the year. Different constellations become visible at different times of the year.

Every constellation seems to revolve around the **Pole Star,** which remains stationary in its position. This is because the Pole Star is directly above the north pole and hence the Earth's axis of rotation always points in its direction (Fig. 24.2).

The **Ursa Major** or the **Great Bear** is the best known constellation and contains seven chief stars making up a pattern known as **The Plough** (Fig. 24.3a). Having located this constellation it can be used to locate the Pole Star and other constellations as shown in Fig. 24.3b.

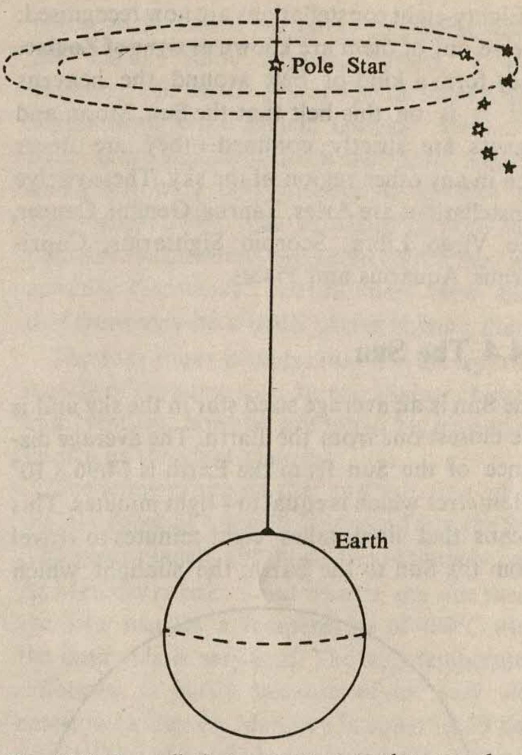


Fig. 24.2 Constellations appear to revolve around the Pole Star due to rotation of the Earth

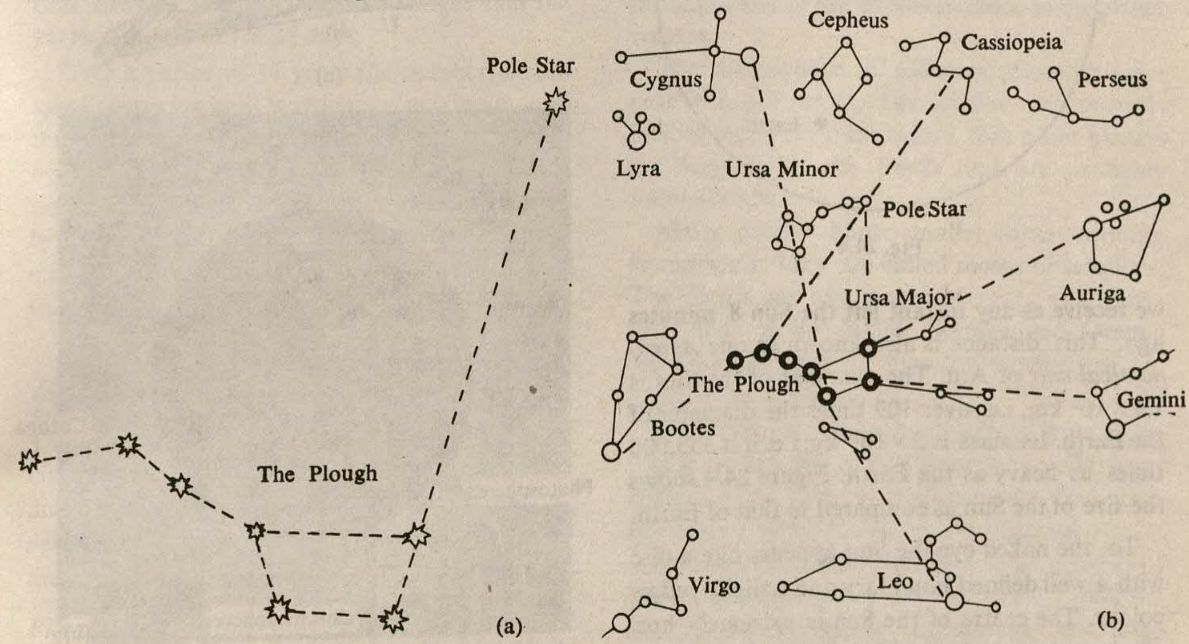


Fig. 24.3(a) The Plough and the position of the Pole Star. (b) Relative positions of some constellations with respect to Ursa Major.

Eighty-eight constellations are now recognised; twelve out of them are known as **signs of Zodiac**. They form a kind of belt around the heavens and it is on this belt that the Sun, Moon and planets are strictly confined—they are never seen in any other region of the sky. These twelve constellations are Aries, Taurus, Gemini, Cancer, Leo, Virgo, Libra, Scorpio, Sigittarius, Capricornus, Aquarius and Pisces.

24.4 The Sun

The Sun is an average sized star in the sky and is the closest one from the Earth. The average distance of the Sun from the Earth is 14.96×10^7 kilometres which is equal to 8 light minutes. This means that light takes eight minutes to travel from the Sun to the Earth; the sunlight which we receive at any instant left the Sun 8 minutes ago. This distance is also known as one ***Astronomical unit*** or A.u. The diameter of the Sun is 1.4×10^6 km, i.e. over 109 times the diameter of the Earth. Its mass is 2×10^{10} kg; i.e. it is 333,000 times as heavy as the Earth. Figure 24.4 shows the size of the Sun as compared to that of Earth.

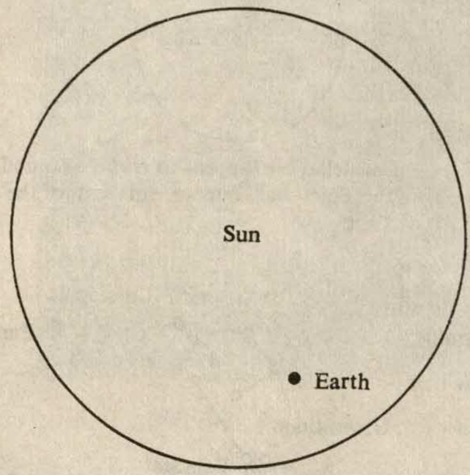


Fig. 24.4

To the naked eye the Sun appears like a disc with a well defined boundary and a slight yellow colour. The centre of the Sun is extremely hot. Its temperature is 14,000,000°C. The centre mainly consists of hydrogen. At this high temperature fusion reactions take place. Atoms of hydrogen fuse into each other to form helium atoms. Some of the mass is changed into energy and enormous amount of light and heat energy are given off.

The surface of the Sun is called the **photosphere**. It is much cooler than the interior but is still extremely hot (6000°C). The photosphere has an irregular bubbly appearance. This is because gases keep rising from inside the Sun. Quite often a cloud of glowing gas erupts from the surface. This is called a **solar prominence**. Prominences are best seen during total solar eclipse. During solar eclipse, when the Moon passes between the Sun and the Earth and blocks the Sun's face, only the luminous gas surrounding it can be seen. This consists of a narrow bright inner layer called the **chromosphere** which is several thousand kilometres wide. The outer layer of gas is called **corona**. It is extremely hot and appears as a pearly halo reaching out millions of kilometres from the Sun.

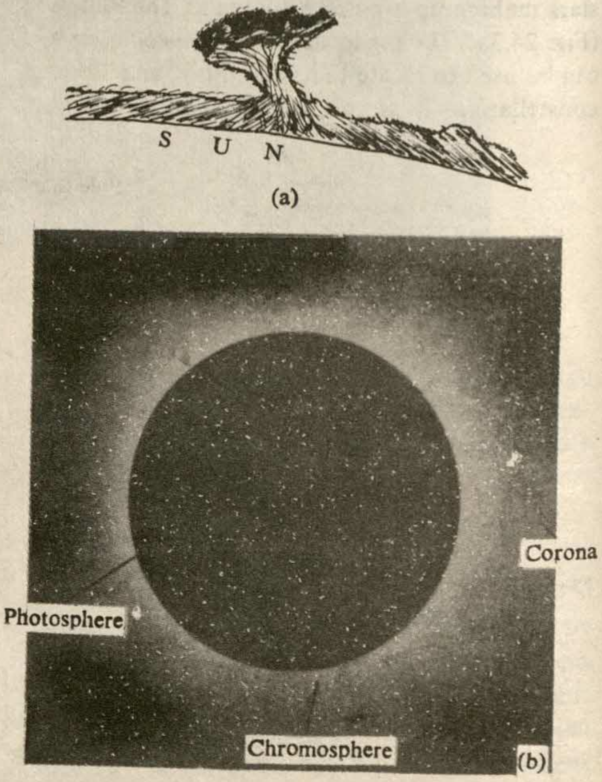


Fig. 24.5(a) Solar prominence. (b) The Sun as seen during a total eclipse.

Sunspots

There are a number of *dark spots* on the surface of the Sun, known as **sunspots** (Fig. 24.6). These appear dark because they are about 2000°C cooler than their surroundings. The spots vary in size. Their diameters vary from 32,000 km to 160,000 km. The observations of the spots has revealed that the Sun rotates about its axis and that the period of rotation is 25 days.

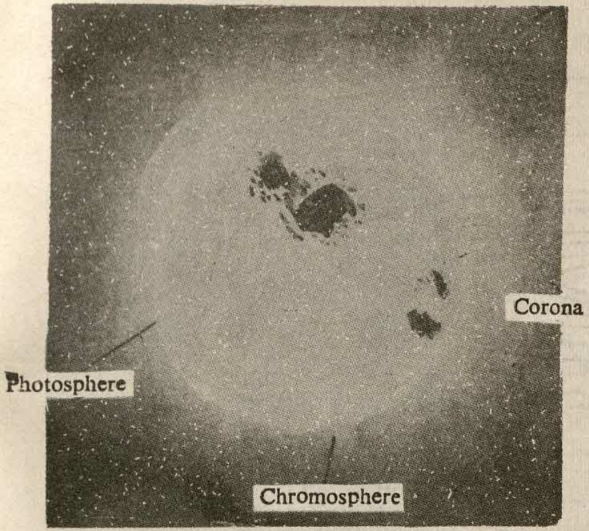


Fig. 24.6 Sunspots

Over a period of 11 years the number of sunspots increases until it reaches a maximum, and then decreases again. This is called the **sunspot cycle**. When the number of sunspots is maximum, the solar flares increase in number and brightness. The flares interfere with the transmission of radio signals around the Earth's surface.

24.5 The Solar System

The Sun moves through space, taking with it a large family of objects such as planets, asteriods and comets. The whole assembly constitutes the **solar system**. The largest and the most important members of the solar system are the planets.

Planets

Nine planets move round the Sun in elliptic orbits, all in the same direction. The nearest planet to the Sun is Mercury, then come Venus, the Earth, Mars, Jupiter, Saturn, Uranus, Neptune, and finally Pluto. The six inner planets were known to the ancient Greeks. Because of their great distances from the Earth, Neptune and Pluto were only discovered in 1846 and 1930 respectively. The existence of both these planets was, however, predicted before they were actually discovered. Astronomers now think that there may be a tenth planet beyond Pluto.

The four inner planets and Pluto are approximately of the same size. Jupiter, Saturn, Uranus and Neptune, however are much bigger and are known as the **giant planets**.

The temperature on the surface of a planet mainly depends upon its distance from the Sun. The giant planets and Pluto are extremely cold. As Mercury rotates about its axis, the side facing the sun reaches a temperature of 400°C while the dark side is very cold. The large temperature difference is partly because of its very slow rotation (a day on Mercury is equal to 59 days on Earth) and partly because there is no atmosphere. A planet's atmosphere is the envelope of air that can trap some of the Sun's heat, preventing rapid rise or fall of temperature as the planet rotates.

The atmosphere of different planets is different from that of the Earth. Also the possible lack of water on them means that other planets are very unlike the Earth and are probably uninhabitable.

Many planets house smaller objects orbiting round them. They are called **moons** or **satellites**. The Earth has one moon, Mercury and Venus have none while Jupiter, Saturn and Uranus have a large number of moons. Jupiter has 16, Uranus 5 and Saturn 15.

The strangest feature of Saturn is its rings. These are thin flat belts of particles possibly consisting of ice. They could also be the fragments of a moon which has never been formed.

Between Mars and Jupiter a large number of minor planets called **asteroids** move round the Sun in their respective orbits. They are large lumps of rocks. So far about 2000 asteroids have been catalogued. The biggest one is **Ceres** whose

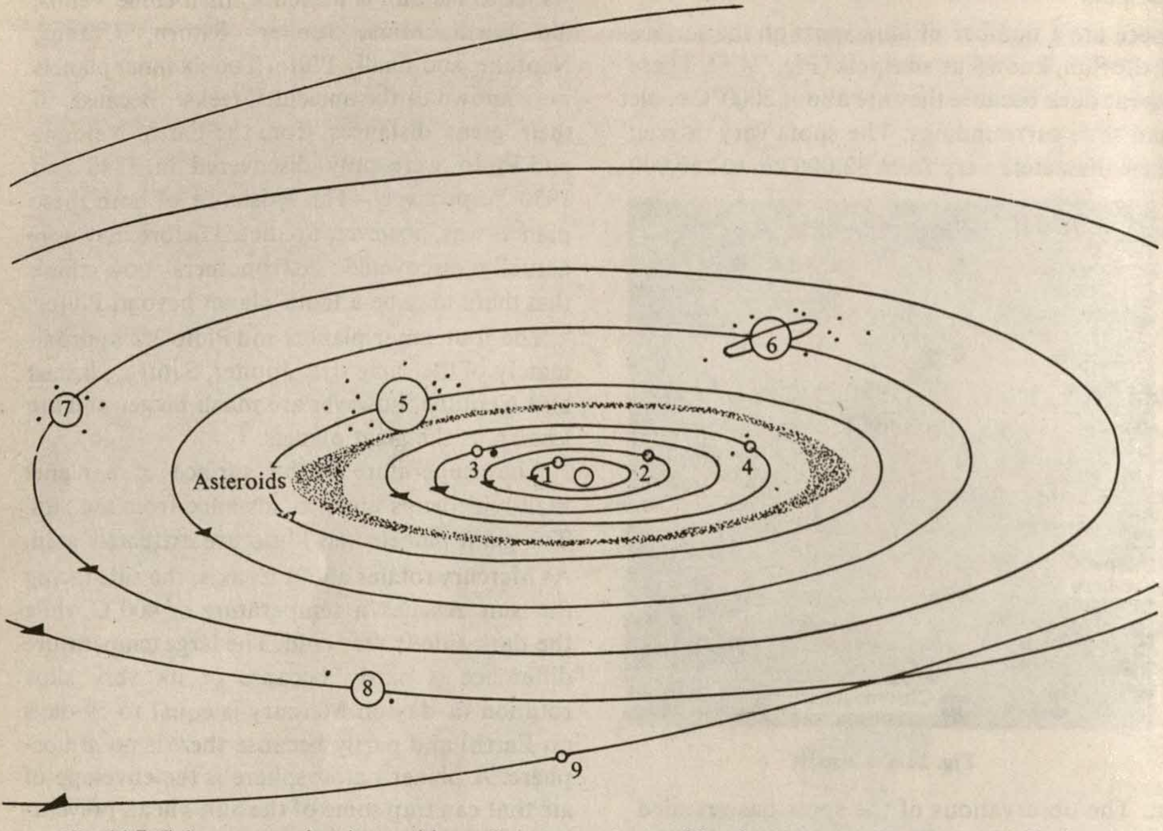


Fig. 24.7 Solar system showing positions of planets and asteroids. 1. Mercury, 2. Venus, 3. Earth, 4. Mars, 5. Jupiter, 6. Saturn, 7. Uranus, 8. Neptune, 9. Pluto

Table 24.1 *Table of the Planets*

Planet	*Distance from Sun in millions of km*	*Diameter in km*	*No of moons*	*Planet's day (earth time)*	*Planet's year (earth time)*
Mercury	58	4880	—	59 days	88 days
Venus	108	12,100	—	243 days	225 days
Earth	150	12,756	1	23 hr 56 min	365¼ days
Mars	228	6790	2	24 hr 37 min	687 days
Jupiter	778	142,800	16	9 hr 50 min	12 yrs
Saturn	1427	120,000	15	10 hr 14 min	29½ yrs
Uranus	2870	51,000	5	10 hr 48 min	84 yrs
Neptune	4497	49,000	2	14 hr	165 yrs
Pluto	5900	3000	1	6 days 9 hr	248 yrs

Note: A day on Venus is longer than its year.

diameter is about 700 km. The smallest asteroid has a diameter of only 3.2 km.

Mercury is very close to the Sun and is only seen near dawn or sunset. It is hard to locate. Venus is a great bright lamp in the evening or morning sky. It is often called the 'evening star' as well as the ‘morning star’. Mars appears red and is known as the ‘red planet’.

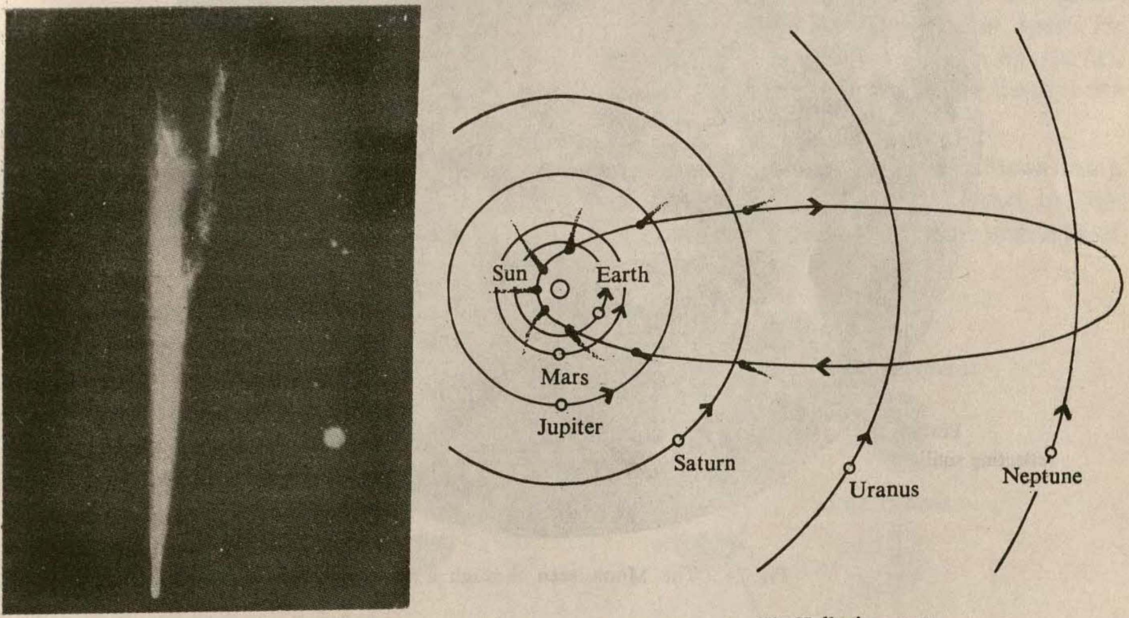
Apart from planets and their satellites, *meteors* and *comets* are other members of the solar system.

Meteors

These are small pieces of matter which travel in the interplanetary space more or less haphazardly. Whenever these bodies come into contact with the earth’s atmosphere, lot of heat is produced due to friction with air and in most cases they burn to ashes. During the process of heating while entering into the earth’s atmosphere, they glow up and look like *shooting stars* which most of you would have noticed while looking at the night sky. Larger meteors called **meteorites** do not burn up completely and reach the ground, often producing craters. Some of these meteorites can be seen in museums.

Comets

A comet is a strange member of the solar system. Large pieces of material moving in the solar system are attracted by the Sun’s, and also by Jupiter’s, gravity and move in a parabolic or very elliptical orbit. Often their paths cross the path of the planets. As they approach the Sun their tails, stretching behind them, away from the Sun, for millions of kilometres become brightly illuminated (Fig. 24.8). Thus comets present a magnificent cosmic sight. A molten and glowing mass, called the head of the comet, is followed by a long bright tail. So far about 100 comets have been discovered. Some comets appear only once while others are periodic in nature. For example, the famous ‘Halley’s comet’ which was first seen by Edmund Halley in 1759, has a period of 76 years (Fig. 24.8). It was last seen in 1910 and will be seen again in 1986.



(a) A comet

(b) Halley’s comet

Fig. 24.8

The Moon

The Moon is our nearest neighbour in space and is the first and only one to be visited by man. It orbits the earth at an average distance of 384,400 km and the period of revolution is 27.3 days. It also takes 27.3 days to complete one rotation about its own axis. Thus the period of rotation about its own axis is equal to the period of

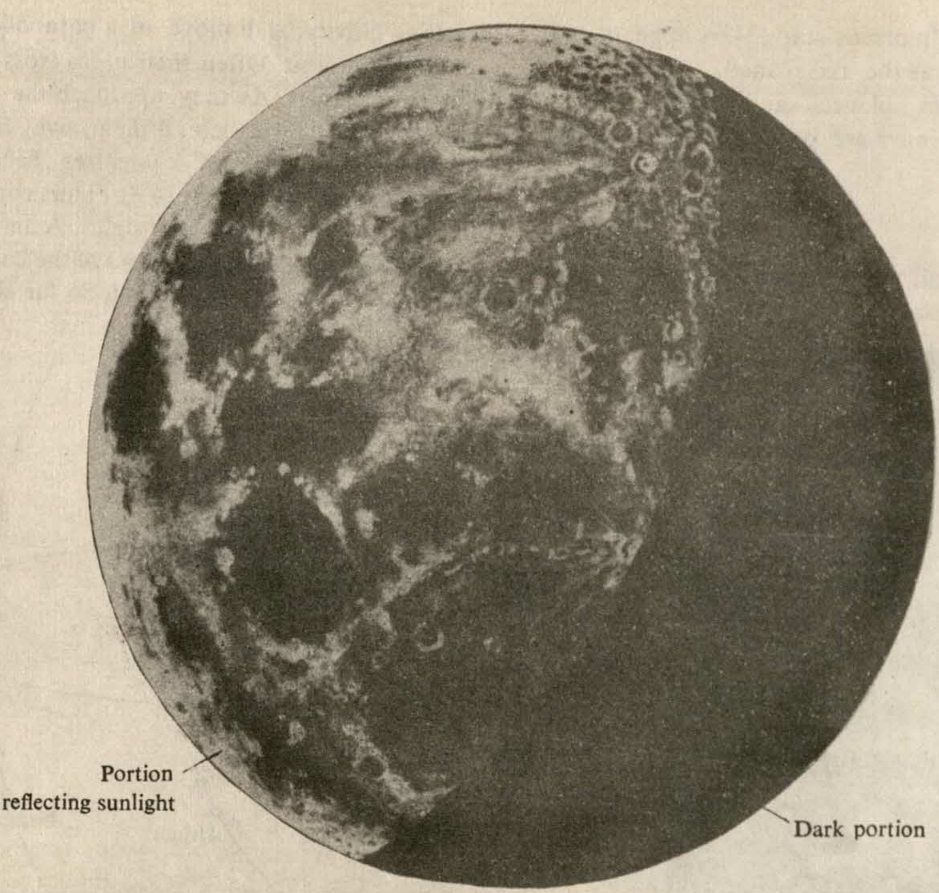


Fig. 24.9 The Moon seen through a telescope.

revolution round the Earth. This is why it always presents the same face to the Earth. Day and night on the Moon last about 14 Earth days. The temperature of the surface that always faces the Earth is 127°C and the temperature of the other side is —153°C. In other words the temperature of day is 127°C and that of night is —153°C.

The Moon is much smaller than the Earth. Its diameter is 3476 km, only 1/4th of the Earth's diameter. It is about 81 times lighter than the Earth. It has been known for a long time that the Moon does not have an atmosphere. Man cannot live there unless he takes his own air supply. The pull of gravity on the Moon is 1/6th of that on the Earth. A man who weighs 90 kg-wt on the Earth would only weigh 15 kg-wt on the Moon and can jump much higher on the Moon. Neil Armstrong, the first man to visit the Moon appeared to hop around on the Moon's surface. The Moon is non-luminous. It shines at night because it reflects the sunlight which falls on it. Moonlight is therefore reflected sunlight.

With the naked eye markings can be seen on the Moon. Galileo who was the first man to use a telescope, thought that these dark areas were seas, because they looked very flat. Actually they are enormous dry plains, though we still call them seas. There is in fact no water on the Moon.

The surface of the Moon is very rocky and rugged. The plains (seas) are often surrounded by very high mountain ranges. The highest mountain on the moon is about 10,000 m high—higher than Mt. Everest. There are wide valleys and small clefts called rills. The Moon is filled with saucer-shaped features called **craters**. There are thousands of them ranging in size from tiny holes to vast plains surrounded by mountain ranges. The largest crater *Baily* is about 300 km in diameter. Some craters are more than 7000 m deep.

Many scientists believe that the Moon was formed at the same time as the Earth. Because it was smaller, it was 'captured' by the Earth and went into orbit around it, becoming its natural satellite.

Phases of the Moon

The changes in the size and shape of the Moon, known as **phases** of the Moon, are caused by changes in the area of the Moon that receives sunlight and reflects it to the Earth. The phases repeat themselves every 29 days. Figure 24.10 shows the phases of the Moon.

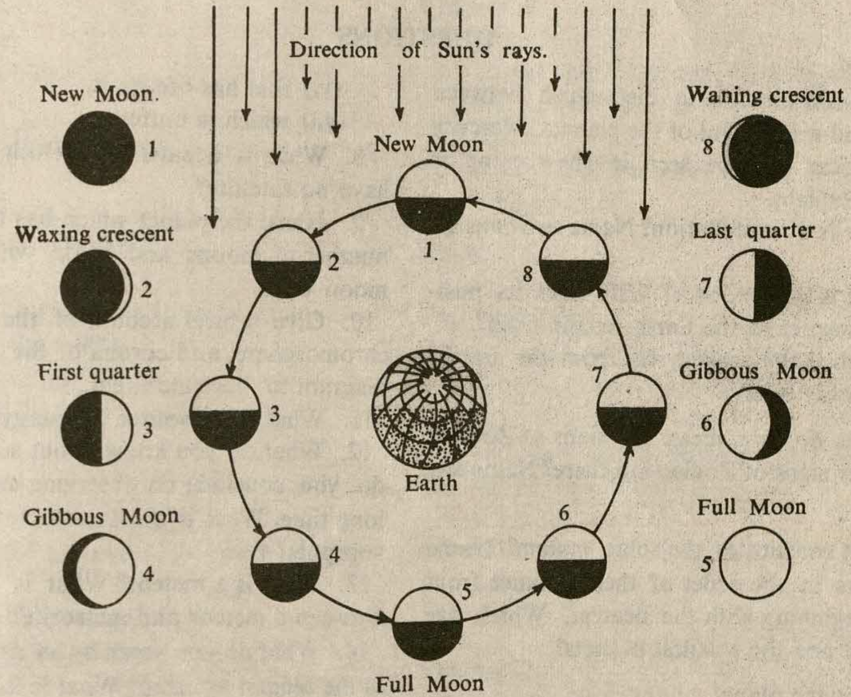


Fig. 24.10 Phases of the Moon

24.6 Exploring Space

Man has long dreamt of journeying beyond the Earth. Man began to investigate space by using rockets to put small objects—called **artificial satellites**—into orbits round the Earth. Russia was the first country to launch an artificial satellite, **Suptnik** I, in October 1957.

In 1962 *Telestar I*, a communication satellite was launched which established the first television link between Europe and America. Now satellites of better designs are being used and have formed an important means of world communications.

In April 1961 Yuri Gagarin, a Russian, became the first man to go up in space. He orbited the Earth once. John Glenn was the first American astronaut. He circled the Earth thrice in the *Mercury* capsule.

The Russians began to study the Moon using a series of space vehicles called *Lunas*. In 1959 Luna 3 sent back to the Earth photographs of the other side of the Moon which man had never seen before

The Americans sent unmanned *Ranger* and *Surveyor* probes towards the Moon in preparation for the manned *Apollo* missions. On 20 July, 1969 Neil Armstrong and Edwin Aldrin became the first men to set foot on the Moon. Their *Apollo 11* mooncraft landed in the Sea of Tranquillity. The Russians, in 1970, sent an 8-wheeled vehicle, *Lunokhod 1* to the Moon. It travelled 10.5 km on the Moon and sent back television pictures and tested the properties of the soil.

In 1971, the Russians made a major breakthrough in establishing a permanent base in space when they launched the *Salyut I* space station. In 1972, Americans launched an experimental space station, *Skylab.* This fell on Earth in 1979. The Russians have since launched six space stations, and in 1980, Russian cosmonauts spent 180 days in orbit in *Salyut 6*.

Americans and Russians have sent many unmanned *space probes* to the planets. The American *Mariner* probes have photographed Mars and Venus; Mariner 10 flew on from Mars to Venus and Mercury. *Viking I* and *II* actually landed on Mars. In 1973 and 1974 two American *Pioneer* probes flew past Jupiter, and a later Pioneer even landed on Venus. So did the Russian *Venera 11* and *12* probes. *Voyager 1* and *2*, the American crafts, flew past Jupiter then on to Saturn to have a close look at it. *Voyager 2* is destined to go on to Uranus and Neptune.

In 1981, Americans achieved a wonder in launching a re-usable *space shuttle*. Upto now space flight has been extremely costly because each manned mission had to use a new rocket and a new spacecraft. The space shuttle is the first space craft which returns to Earth and can be reused.

QUESTIONS

1. How is it possible to distinguish between a planet and a star? Out of the planets, Mercury and Venus can only be seen in the evening or morning. Explain.

2. What is a constellation? Name two constellations.

3. What is the Pole Star? Why does its position with respect to the Earth remain fixed?

4. Which is the nearest star from the Earth? How far away is it?

5. What do you mean by signs of Zodiac? How many signs of Zodiac are there? Name any three.

6. What constitutes the solar system? Name the planets in the order of their distance from the Sun beginning with the nearest. Which are the biggest and the smallest planets?

7. Name the planet

(i) nearest to the Earth;
(ii) nearest to the Sun;
(iii) which has rings round it;
(iv) farthest from the Sun;
(v) which is largest;
(vi) that has life on it;
(vii) which is hottest

8. What is a satellite? Which two planets have no satellite?

9. Name the planet which has the maximum number of moons and those which have one moon each.

10. Give a brief account of the photosphere, chromosphere, and corona of the Sun. Draw a diagram to illustrate them.

11. What is the source of energy in the Sun?

12. What do you know about sunspots? What do you conclude on observing sunspots over a long time. What is the duration of the cycle of sunspots?

13. What is a meteor? What is the difference between a meteor and meteorite?

14. What do you mean by an asteroid? Which is the biggest asteroid? What is its diameter?

15. What is a comet? After how many years is 'Halley's comet' observed.

16. In what respect are comets strikingly different from planets?

17. Is a shooting star really a star? If not what is it?

Answers to Numerical Problems

Chapter 1

2. (a) 1, 2 and 4ml
3. (a) 60cm^2 (b) 250cm^2 (c) 920cm^2
4. 72cm^2
5. (a) 25cm^2 (b) 24cm^2 (c) 21cm^2 (d) 31.83cm^2
6. (a) 40m^3 (b) 40,000 litres; 0.18m^3
8. 1700 kg/m^3
9. 6.05×10^{24} kg
10. 1950 kg
12. 222.5; 40; 10.5; 2.25
14. 11.3 g/cm^3
15. 0.88 g/cm^3
16. (a) 25cm^3 (b) 0.8 g/cm^3 (c) 0.8 g
19. (a) $\sqrt{2}$ s (b) $2\sqrt{2}$ s (c) 4 s
21. (a) 1.41sec (b) 2.0sec
24. 0.05cm; 0.001cm
27. 3.02mm; 2.52mm

Chapter 2

1. 20m/s
2. 0.0122 cm/s; 465.5 m/s
4. 16.67m/s; 9.7 km and 15.5° south of east
7. 80m/s^2
8. (c) 25cm/s^2 (d) 600m
9. (a) 120 cm/s^2 (b) 15m
11. 135 m
13. 9.88 m/s^2 ; 4.5 s

Chapter 3

3. 350 N
4. 20 N from east to west
5. 8.6 m/s
6. (a) double (b) double
10. one - half
11. 4 kg and 2 kg ; 1.33 m/s^2
12. 10^{-30} kg
14. 4.9×10^6 J
15. 294 J
20. (a) 2 m/s^2 (b) 10^5 J (c) 10^5 J (d) 10^4 W
22. 9×10^5 J/min or 15,000 W
27. 10m/s^2

Chapter 4

8. 105 gf
9. 10 kgf and 6 kgf; the man at the lighter end should carry it at a point 1 m from that end.
10. 0.5 m from the pivot on the side of the 10 kg boy.

Chapter 5

3. (a) 16 gf/cm^2 (b) 8 gf/cm^2
4. 1960 N/m^2
13. (a) 3 gf/cm^2 (b) 7.5 gf/cm^2 (c) 60 gf acting downward (d) 150 gf acting upward (e) 90 gf acting upward
16. (a) 40 cm^3 (b) 2.5 g/cm^3 (c) 1.25 g/cm^3
17. 2.5 g/cm^3 ; 1 cm^2
19. 9/11
22. 90 kgf
26. −41°C

Chapter 6

3. 10^{-6} g ; 2×10^{15}
4. 2×10^{-7} cm

Chapter 7

14. (a) 40°C (b) 12 cm

Chapter 9

7. 2760 J
8. 30°C
10. 127.6 J/kg °C

11. 22.16 °C
18. 342.7 kJ/kg
25. 86 J
26. 15,143 J
27. 32.67 °C
28. 31,200 J (a) 2 min 20 sec (b) 15 min
29. 2,154,912 J/kg

Chapter 10

5. 5 cm
6. 10 cm

Chapter 11

4. 70°
9. 3m ; 4m
10. 0.8 m
11. 7 ; 2 ; 4; $n=\frac{360}{6}$ 1

19. (a) 4cm behind the mirror (b) 45cm
20. 15 cm ; 60 cm in front of the mirror; real and inverted ; 3

Chapter 12

4. 1.5
8. 48° 16′ ; 1.49 ; 64° 4′

Chapter 13

5. 26.7 cm on the other side of the lens ; 3.3 cm tall ; real and inverted ; 2/3.
6. +3.33 D ; —25 cm ; concave
13. (a) Concave lens of —1D power
    (b) No lens
15. Virtual, erect and 1 cm high ; 20 cm from the lens on the same side.
16. 6

Chapter 14

4. 1.29 m
5. (b) 5 m ; 1 Hz ; 5 m/s
7. 1428.6 MHz
8. 187.5 to 555.6 m
9. 3.75×10^5 km

Chapter 15

7. 311.1 m/s
8. 1700 m
11. 216.75 m
15. 0.5 s
16. 2250 m
17. (a) 4m (b) 2 Hz (c) 8m/s
22. 340m

Chapter 17

10. 6C

Chapter 18

5. (i) 0.2A (ii) 0.83 A
6. (i) 0.4 A (ii) 1.07 V
   (iii) 0.27 A (iv) 0.289 W
7. (i) 1.8 A (ii) 3 A
9. 6Ω ; 0.67Ω
10. (i) 1210Ω ; 806.7 Ω, 484Ω
    (ii) (2/11) A ; (3/11) A ; (5/11) A
    (iii) 242 Ω ; (iv) 0.909 A
    (v) 60,000 J
11. (i) No deflection in any meter
    (ii) Both *A* and *B* record 3 A
    (iii) *A* records 6 A, *D* records 4A
12. (i) 0.14 Ω (ii) 0.35 V
14. 12,000 J
15. 1210Ω
16. 1 kWh=3,600,000 J
20. Rs. 48
21. 2 : 1
22. Rs. 200
27. 5Ω; 2.5Ω

Chapter 20

12. (i) 0.1V (ii) (10/99) Ω in parallel
    (iii) 0.99 A
15. (a) 0.08V (b) 960 Ω
    (c) 0.08 Ω or (80/998) Ω
16. (a) 3600 Ω (b) 0.404Ω

Chapter 21

13. 12.5 kW ; 1.25W
16. 60V ; 0.2V
18. (b) 25V

Chapter 23

8. 2.5 g
9. 1800 years
10. (i) 86 p and 136 n
    (ii) 84 and 226
11. 90 and 226
12. α, β, γ
16. 3 hours

Modern Secondary Physics

This book has been written for secondary students following the ICSE pattern and is based on the new syllabus. It takes into consideration not only the topics but also the *objectives* set by the syllabus.

In keeping with the modern methods of teaching physics, considerable emphasis has been laid on experimental work and on the applications of physics in day-to-day life and in modern industries.

The text has been supplemented by a number of 'Activities' which the student can easily perform with very simple apparatus.

A simple and concise style has been followed throughout the book, and all efforts have been made to weed out concepts and information irrelevant to the students at this stage.

Other Science Books following the new ICSE syllabus

New Secondary Physics Workbook (revised edition)
I.B. Kakar and B.G. Pitre

New Secondary Lab Manual : Physics (revised edition)
I.B. Kakar and B.G. Pitre

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